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TECHNICAL REPORT E-72-32

ANNOTATED BIBLIOGRAPHY OF EXPLOSIVE EXCAVATION RELATED RESEARCH

July 1972

U. S. Army Engineer Waterways Experiment Station
Explosive Excavation Research Laboratory
Livermore, California

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Preface

The U.S. Army Engineer Waterways Experiment Station (USAEWES) Explosive Excavation Research Laboratory (EERL) was the USAEWES Explosive Excavation Research Office (EERO) prior to 21 April 1972. Prior to 1 August 1971 the organization was known as the USAE Nuclear Cratering Group.

This annotated bibliography was compiled under the direction of MAJ Richard H. Gates. Those who assisted in the compilation were MAJ Richard W. Mattes, SP4 Richard K. Knowles, Ralph E. Burkett, and William T. Fisher.

During the time the reports in this bibliography were written the following officers of the Corps of Engineers served as Director of the Nuclear Cratering Group and the Explosive Excavation Research Laboratory:

Director (with grade during tenure)

LTC Ernest Graves, Jr. (July 1962-July 1964)
LTC Walter J. Slazak (July 1964-June 1967)
LTC Maurice K. Kurtz, Jr. (June 1967-January 1968)
LTC Bernard C. Hughes (January 1968-June 1969)
COL William E. Vandenberg (June 1969-January 1971)
LTC Robert L. LaFrenz (January 1971-July 1972)
LTC Robert R. Mills, Jr. (July 1972-).

Abstract

This bibliography contains a description of all reports prepared by the USAE Nuclear Cratering Group (NCG), the USAE Waterways Experiment Station Explosive Excavation Research Office (EERO), and the USAE Waterways Experiment Station Explosive Excavation Research Laboratory (EERL) from Fiscal Year 1962 through Fiscal Year 1972. The reports address themselves to the many topics associated with the use of chemical and nuclear explosives in excavation projects, and each is described by a brief summary or abstract. Indexing is by subject, author, title, and report number.

Conversion Factors

British units of measurement used in this report can be converted to metric units as follows:

Multiply	By	To obtain
inches	2.54	centimeters
feet	0.3048	meters
cubic feet	0.02832	cubic meters
cubic yards	0.764555	cubic meters
pounds	0.4535924	kilograms
pounds per square inch	0.00689476	meganewtons per square meter
pounds per cubic foot	16.02	kilograms per cubic meter
Fahrenheit degrees	5/9	Celsius or Kelvin degrees[a]
foot-pounds	0.138255	meter-kilograms

[a]To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

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TECHNICAL REPORT E-72-32
ANNOTATED BIBLIOGRAPHY OF EXPLOSIVE EXCAVATION RELATED RESEARCH

I. Introduction and Summary

A. PURPOSE

The Explosive Excavation Research Laboratory (EERL),* through its predecessor organization, the Nuclear Cratering Group (NCG), has served since 1962 as the Corps of Engineers activity responsible for engaging in research to determine the feasibility, costs, and engineering practicability of using large-yield chemical high explosives and nuclear explosives for civil construction. Effective 1 August 1971, EERL was established as an activity of the U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi. EERL's location at the Lawrence Livermore Laboratory (LLL) in Livermore, California, facilitates technical interchange and continues a long-standing Corps of Engineers association with LLL Plowshare research activities—research directed toward peaceful applications of nuclear explosives under the auspices of the Division of Peaceful Uses of Nuclear Explosives of the U.S. Atomic Energy Commission (AEC).

Prior to 1969, explosive excavation research was principally concerned with nuclear explosives, and chemical high-explosives were used for modeling nuclear excavation concepts. Since 1969, the direction has been toward the development of both chemical and nuclear explosive excavation design techniques and engineering procedures which can be used on a wider range of sizes and types of civil engineering excavation projects. Flexibility and adaptability in design procedures, engineering practicability, and cost competitiveness with conventional excavation methods are the guidelines for the current research effort. Military-related explosive excavation research emphasizes high-priority military requirements. The nuclear modeling experience within the Laboratory is now being applied to the general problem of simulation of ADM cratering detonations with chemical explosives. The Laboratory's unique background in nuclear and chemical explosive studies and testing qualifies it to conduct research in many explosion related phenomena and explosion engineering techniques of value to civil engineers and to the Army.

*During the period 1 August 1971 to 21 April 1972 the organization was known as the Explosive Excavation Research Office; however, on 21 April 1972 the "Office" was changed to "Laboratory."

B. ORGANIZATION

Section II of this bibliography lists by type and numerical designation all NCG/EERL prepared or sponsored reports through FY 72. Each listing gives a brief summary or abstract of the report, author's name, and publication date.

To increase the usefulness of this bibliography, all reports have been cross-indexed by subject (Section IIIA), by author (Section IIIB), and by title (Section IIIC).

C. CLASSES OF REPORTS

1. Technical Reports (TR's)

Reports prepared by NCG/EERL personnel covering research and development activities considered pertinent for wide distribution. These reports are distributed to all pertinent Corps of Engineer agencies and to other specific government agencies.

2. Technical Memoranda (TM's)

Documents prepared by NCG/EERL personnel for internal use only. External distribution of these memoranda is made only in special cases to satisfy technical coordination requirements.

3. IOCS Memoranda

Reports relating to Interoceanic Canal Studies generated by NCG as a group. Only a limited number of copies of these reports was made.

4. PNE Reports

Reports published under the auspices of the AEC Peaceful Uses of Nuclear Explosives Program (PNE). The PNE reports published by NCG/EERL cover primarily the results of major NCG/EERL cratering experiments, NCG technical programs included as a part of AEC nuclear cratering experiments, and technical feasibility studies of general interest to personnel involved in the Plowshare program.

5. Miscellaneous Reports

Reports published by other agencies covering research and development activities sponsored and funded by NCG/EERL.

6. Articles

Articles published by members of the group in trade publications.

D. AVAILABILITY

TR's and PNE reports are available through National Technical Information Service, U.S. Department of Commerce, Springfield, Virginia 22151, or the Defense

Documentation Center, Cameron Station, Alexandria, Virginia 22314. Organizations desiring copies of TM's or IOCS Memos should contact the Director, U.S. Army Engineer Waterways Experiment Station Explosive Excavation Research Laboratory, P.O. Box 808, Lawrence Livermore Laboratory, Livermore, California 94550. Other reports can be obtained through the National Technical Information Service in the same manner as TR's and PNE's.

II. Reports

A. Listing of Reports

The following is a listing of all reports and articles, grouped numerically in the following categories:

1. Technical Reports (TR's)
2. Technical Memoranda (TM's)
3. IOCS Memoranda
4. PNE Reports
5. Miscellaneous Reports
6. Articles

1. Technical Reports (TR's)

TR	Subject	Date published
TR-1 (DASA) 1669	Military Engineering with Nuclear Explosives	Jun 66
TR-2	Nuclear Construction Engineering Technology	Sep 68
TR-3	Project ZULU II, Phase I: Single-Charge Calibration Series	Nov 68
TR-4 (Secret)	Report of Farout Fallout Collection for Projects CABRIOLET and BUGGY	Dec 69
TR-5	Project ZULU II: Laboratory-Scale Row-Charge Cratering Studies	Nov 68
TR-6	Nuclear Excavation Design of a Transisthmian Sea-Level Canal	Oct 68
TR-7	(Not used—changed to PNE 527.)	
TR-8	The Corps of Engineers Nuclear Explosives Studies for Civil Construction	Oct 68
TR-9	(Not used.)	
TR-10	Construction Techniques and Costs for Emplacement of Nuclear Explosives in Disturbed Media	Mar 69
TR-11	Nuclear Explosive Quarrying Potential within North Pacific Engineer Division	May 70
TR-12	Conventional Excavation Methods and Costs for Use in Feasibility Studies of Nuclear and Conventional Earthwork Projects	Jun 69
TR-13	Quarrying with Nuclear Explosives	Dec 70

TR	Subject	Date published
TR-14	Natural Rubble Slopes and Their Relevance to Crater Fallback Slopes	Sep 69
TR-15	Empirical Study of Behavior of Clay Shale Slopes	Dec 70 (vol. 1) Jul 71 (vol. 2)
TR-17	Project Tanktrap: A Field Evaluation of Nuclear Terrain Barriers	Jun 69
TR-18	A Simple Technique to Determine the Size Distribution of Crater Fallback and Ejecta	Mar 70
TR-19	The NCG Fallout Scaling Model: A Graphic-Numerical Method of Predicting Fallout Patterns for Nuclear Cratering Detonations	Jan 70
TR-21	Explosive Excavation Technology	Jun 71
TR-22	Fallout Prediction Procedure for Subsurface ADM's	Sep 71
TR-23	Project Tugboat: Explosive Excavation of a Harbor in Coral	Feb.72
TR-25	Study of Explosives for Lunar Applications	Feb 71
TR-26	Construction of Underground POL Storage Facilities with Nuclear Explosives	June 72
TR-27	Seepage Characteristics of Explosively Produced Craters in Soil and Rock	Sep 70
TR-28	Project TRENCHER: Evaluation of Aluminized Blasting Agents for Cratering and Hole Springing	Nov 70
TR-29	Initiation of Failure in Slopes in Overconsolidated Clays and Clay Shales	Jan 71
TR-30	Hydrologic Transport of Radionuclides from Nuclear Craters and Quarries	Sep 70
TR-31	Cratering in Layered Media	In pub
TR-32	Annotated Bibliography of Explosive Excavation-Related Research	July 72
TR-33	Project SERGIUS NARROWS—Summary of Tests on Liesnoi Island, Alaska, 1970	Nov 71
TR-34	Project TRINIDAD: Explosive Excavation Tests in Sandstone and Shale	June 72
TR-35	MIDDLE COURSE I Cratering Series	Jun 71
TR-36	Analytical and Graphical Methods for the Analysis of Slopes in Rock Masses	Jul 71
TR-37	Summary of Time-Delayed Row-Charge Cratering Experiments, Site 300, 1970	May 71
TR-38*	Project Pre-GONDOLA III Phase III: Connection of a Row Crater to a Reservoir	Aug 71
TR-39	A Revised Empirical Approach to Airblast Prediction	Nov 71
TR-40	Prediction of Ground-Shock-Induced Airblast Overpressures for Subsurface Explosions from Peak Vertical Spall Velocity	Nov 71

*Published also as PNE-1120.

2. Technical Memoranda (TM's)

TM	Subject	Date published
65-1	Computer Code Input and Printout Interpretation for the A. V. Shelton Fallout Model (FLIP)	Mar 65
65-2	Pre-SCHOONER Ground Surface Motion Study	Apr 65
65-3	Surface Geology of the Pre-SCHOONER II Area	May 65
65-4	Postshot Field Investigations, Buckboard Mesa, Nevada Test Site	Aug 65
65-5	Analysis of the Knox Fallout Prediction System (KFOC)	May 65
65-6 (Secret-RD)	Method for Predicting Dose Rate Pattern at Various Times for Multi-Detonation Excavation Programs (U)	Jun 65
65-7	Ground Water Contamination Study and Evaluation	Jul 65
65-8	Study of the Shape and Slope of Explosion-Produced Craters	Nov 65
65-9	Project ZULU: A One-pound High Explosive Cratering Experiment in Scalped and Remolded Desert Alluvium	Oct 65
65-10	Analysis of A. V. Shelton Fallout Prediction System (FLIP CODE)	Jul 65
65-11	Geologic Examination of the Access Shaft and Explosive Cavity for Project Pre-SCHOONER II	Nov 65
65-12	A Preliminary Model for Analysis of Nuclear Crater Slope Stability in Homogeneous Medium	Nov 65
65-13	A Preliminary Assessment of Overexcavation as a Possible Solution to Potential Slope Stability Problems	Nov 65
65-14	(Not used—see PNE-5006.)	
65-15	Preliminary Report of the Analytic Study of Tide-Induced Currents in a Sea-Level Canal	Nov 65
66-1 (Secret-RD)	Investigations of the Resulting Crater Slope and Local Fallout Radioactivity to be Expected When a Nuclear Device is Buried at a Scaled Depth Less than Optimum and the Yield Varied to Give the Required Crater Depth (U)	Jan 66
66-2	The Knox Fallout Prediction System's (KFOC) Response to Changes in Input Parameters Which Define the Activity-Particle Size Distribution	Jan 66
66-3	Summary of the Opinions of the Technical Associates to the Atlantic-Pacific Interoceanic Canal Study Commission, and Opinions of the Consultants to the Waterways Experiment Station which are Related to the Nuclear Excavated Cuts	Feb 66 (Limited distribution)
66-4	Early Estimates of Radioactivity in the Fallout Field	Feb 66
66-5	Phenomenology of the Formation of a Crater by Detonation of a One Pound Charge Buried at a Depth of Burst of Two Feet in the ZULU II Moist Sand	Feb 66
66-6	The Effects of Inhomogeneities in a Controlled Sand Medium on Small Scale High Explosive Experiments	Aug 66
66-7	Consolidated Report: Operation Breakup, FY 66, Ice Cratering Experiments, Blair Lake, Alaska	Nov 66
66-8	Cloud Dimensions for Cratering Explosions	Sep 66

TM	Subject	Date published
66-9 (Secret-RD)	Study on Tactical Fallout Prediction Method for the Military Engineering Application of Nuclear Explosives (U)	Oct 66
66-10	(Not used—see PNE-1100.)	
66-11	A Computer Solution Using the Pillsbury Method for Computation of Tides and Currents in Nuclear Excavated, Conventionally Excavated or Combination Channels	Jul 66
66-12	Stem Design for Tactical Emplacement of Nuclear Explosives	Aug 66
66-13	A Model of the Formation of the NEPTUNE Crater	Sep 66; revised: Apr 67
66-14	Analysis of Surface Motion Phenomena of One-pound ZULU II Charges of Varying Depth of Burst	Jul 66; revised: May 67
66-15	Analysis of the Phenomena Within the Immediate Crater Area Resulting from the Detonation of One-pound ZULU II Charges	Apr 67
66-16	Tidal Hydraulics—Preliminary Report on the Results of Tidal Hydraulic Computations (Pillsbury Method)	Oct 66
66-17	Tidal Hydraulics—Hydraulic Characteristics of Tidal Channels Produced by Nuclear Explosive Techniques	Oct 66
66-18	Variation of Project ZULU II Crater Dimensions Versus Medium Properties	Oct 66
66-19	Zone of Bulking, Project SULKY	Nov 66
66-20	A Report of the Scope and Preliminary Results of Project Pre-GONDOLA I	Dec 66
67-1	Predicted Dose Rates within the Nuclear Crater and Lip Area	Feb 67
67-1a (Secret-RD)	Predicted Dose Rates within the Nuclear Crater and Lip Area (U)	Feb 67
67-2	Channel Criteria for the Evaluation of the Tides and Currents in a Nuclear Excavated Sea-Level Canal	Jan 67
67-3	Engineering Properties of Craters	Mar 67
67-5	An "L" Shaped Row Charge Cratering Experiment	Mar 67
67-6	The Euclid Code, A Computer Program for the Calculation of the Nuclear Explosive Requirements for a Nuclear Excavated Channel	Apr 67
67-7	Trace Elements in Common Rock Types and Their Relative Importance in Neutron-Induced Radioactivity Calculations	Jan 67
67-8	Pre-SCHOONER Target Horizontal Displacement and Velocity Histories	Jul 67
67-9	A Report of the Scope and Preliminary Results of Project Pre-GONDOLA II: Row Charge Cratering Experiment	Aug 67
67-10	Pre-Gondola Seismic Decoupling Series	Jul 67; revised: Jan 68
67-11	(Not used.)	
67-12	(Not used.)	
67-13	(Not used.)	

TM	Subject	Date published
67-14	Explosively Producing an Embankment Across a Narrow, Steep-Walled Canyon	Sep 67
67-15	(Not used.)	
67-16	Nuclear Excavation Feasibility Study, Construction of Rockfill Embankment for a Dam	Sep 67
67-17	Site Selection Investigation for a High Explosive Cratering Experiment in Varying Terrain	Sep 67
67-18	Conceptual Study: Dam Construction in Dimond Gorge, Western Australia	Oct 67
67-19	Concepts and Techniques of Seismic Site Calibration for Project Pre-GONDOLA	Dec 67
67-20	Project ANGLEDOZER Site Selection Investigations	Nov 68
68-1	The Wind Code: A Computer Program for Calculating and Summarizing Wind Hodographs	Feb 68
68-2	Concepts of Nuclear Excavation	Feb 68
68-3	Project Pre-GONDOLA II: Physical Characteristics Studies, Fort Peck Dam Embankment	May 68
68-4	Effective Yields for Effects Predictions for Row and Array Emplacement of Surface and Buried Nuclear Charges	Feb 68
68-5	Results of Array Modeling Experiment to Produce Flat Slopes Using the Two-Pass Concept	Mar 68
68-6	Summary of Nuclear Crater Slope Stability Empirical and Analytic Studies, FY 1963-FY 1968	Apr 68
68-7	Preliminary Assessment of Nuclear Crater Slope Stability as Related to the Interoceanic Canal Studies	Apr 68
68-8	A Computer Program for Analyzing the Stability of Nuclear Crater Slopes	Jul 68
68-9	Project ZULU II: Summary Report of Flat-Slope Array Experiments	Nov 68
68-10	Preliminary Report: NCG Pre-GONDOLA III Sixty-Four Pound TNT Flat-Slope Experiments Conducted at Fort Peck, Montana	Jul 68
68-11	Sensitivity of Nitromethane and Survivability of a One-Ton Aluminum Sphere Under High Pressure Loading	Oct 68
68-12	BORHOL: A Computer Program to Compile Geological Engineering Parameters from NX Borehole Camera Data	Jan 69
68-13	Analysis of the Feasibility of Channel Improvement by Nuclear Excavation at Sergius and Whitestone Narrows, Alaska	Nov 68
68-14	Analysis of Vesic Crater Modeling Experiments	Nov 68
68-15	Analysis of the Grid Photography Technique as a Means of Determining the Size Distribution of Crater Fallback and Ejecta	Jan 69
68-16	Preliminary Assessment of the Postshot Engineering and Construction Requirements for the Cape Keraudren Port Development Project	Jan 69
69-1	Preliminary Estimation of the Postshot Interval Required for Radionuclide Concentration in Family Cow Milk to Decay to Acceptable Levels	Jan 69

TM	Subject	Date published
69-2	(Not used—cancelled.)	
69-3	Project ZULU II: Harbor Modeling Study	Feb 70
69-4	(Not used—cancelled.)	
69-5	A Method for Predicting Final Rubble Size in Explosive Excavations	Apr 70
69-6	General Site Selection Study	Jan 70
69-7	Predicted Exposure Rates Within the Nuclear Crater and Lip Area	May 69
69-8	(Not used—changed to NCG-TR-28.)	
69-9	Estimating the Internal Radiation Dose to Man Via Major Ecological Pathways for Plowshare Nuclear Cratering Events	Aug 70
69-10	(Not used—changed to IOCS Memo.)	
69-11	Summary or Explosive Cratering Performance Tests Conducted at Site 300 During 1969	Jul 70
69-12	Lunar Excavation with Buried Explosives	Jan 70
70-1	Analysis and Reevaluation of Bulking Factors	Mar 70
70-2	(Not used—Cancelled—Changed to TR-39.)	
70-3	Chemical Explosive Excavation State-of-the-Art	Jan 71
70-4	Explosive Excavation on the Moon: The Lunar Surface, Lunar Explosives and Emplacement, Terrestrial Modeling Techniques, and Seismic, Blast, and Ejecta Effects	Jan 71
70-5	Conceptual Lunar Applications of Chemical Explosives	Feb 71
70-6	Training for Chemical Explosives Employment for Lunar Application	Aug 70
70-7	Analysis of Hydrologic Transport of Tritium	Apr 71
70-8	Rainfall Leaching Model for Fallout Tritium: The Rain Code	Feb 71
70-9	(Not used—Cancelled)	
70-10	(Not used—Cancelled—Changed to TR-40.)	
70-11	Summary of Underwater Cratering Tests Conducted at Site 300 during 1970	Aug 71
70-12	Feasibility of Constructing a Military Harbor Using Nuclear Explosives	Mar 71
70-13	A Method for Estimating the Bulking Factor of Rubble in Explosive Excavation	Apr 71
70-14	Review of Material on Predicting Underwater Shock Wave Dynamics and Safe Distances for Underwater Swimmers	Mar 71
70-15	User's Manual for Crater Data: A Computer Code for Analyzing Experimental Cratering Tests	Oct 70
71-1	Cost Experience of Explosive Excavation Experiments	Feb 72
71-2	Explosive Cavity Construction by Drilling and Underreaming	Dec 71
71-3	Media Classification for Explosive Excavation	Sep 71
71-4	Wedge Slope Stability Analysis of Explosive Excavations	Dec 71
71-5	Groundwater and Piezometric Records for Pre-GONDOLA Craters	May 71
71-6	Results of Cylindrical Charge Tests Conducted at Site 300, 1970	Jan 72

TM	Subject	Date published
71-7	Design and Analysis of Spherical Aluminum Containers Used in the Middle Course Cratering Experiments	Feb 71
71-8	Tree Damage from the TRINIDAD Cratering Experiments C-1, C-2, and C-3	Mar 72
71-9	Underwater Explosive Excavation Modeling Tests	Jan 72
71-10	Project MINI-MOUND	Mar 72
71-11	A Study of Emplacement Construction Techniques for the Explosive Excavation of SERGIUS NARROWS	Aug 71
71-12	Explosive Excavation Test Facility, Site 300	Dec 71
71-16	Prediction of Fallout from Buried Nuclear Devices (U)	Jan 72
71-17	Shock Wave Interaction and Near-Surface Cavitation, Project Tugboat	Apr 72
71-29	Simulation of Subsurface Nuclear Explosions with Chemical Explosives	Mar 72
71-30	User's Manual for CPM Computer Code	Jan 72
72-1	User's Manual for MIDOL Cost Minimization Computer Code	Feb 72
72-2	Anthology on Explosive Excavation, 1968-1971	Jan 72
72-4	User's Manual for MITIM Time Minimization Computer Code	Apr 72

3. IOCS Memoranda

IOCS Memo	Subject	Date published
3	Report of Petrographic Analyses on Rock Samples from Routes 17 and 25	Nov 65
4	Preliminary Report on the Analytic Study of Tide Induced Currents in a Sea-Level Canal	Nov 65
5	List of Notes and Publications on Soils and Geologic Data Pertaining to the IOCS Engineering Feasibility Studies Available from the Personal Library of Thomas F. Thompson, Consulting Engineering Geologist	Nov 65
6	Preliminary Alignment Investigation: Route 17	Dec 65
7	Preliminary Alignment Investigation: Route 25	Dec 65
8	Preliminary Alignment Investigation: Route 17	Mar 66
9	Preliminary Alignment Investigation: Route 25	Mar 66
10	Second Report of Petrographic Analyses of Rock Samples from Routes 17 and 25	Apr 66
11	Geomorphic Analysis of Route 17	May 66
12	Preliminary Alignment Investigation: Route 17	Jun 66
13	Nuclear Excavation Design (Preliminary): Route 25	Jun 66
14	Geomorphic Analysis of Route 25	Jul 66
15	Nuclear Excavation Design (Preliminary): Route 17	Sep 66
16	Nuclear Excavation Design (Preliminary): Route 25	Sep 66
17	Special Report 1966: Construction of an Isthmian Sea-Level Canal by Nuclear Methods: Route 8, Nicaragua-Costa Rica	Dec 66
18	Nuclear Excavation Design (Preliminary): Route 17	Dec 66
19	Nuclear Excavation Design (Preliminary): Route 25	Dec 66

IOCS Memo	Subject	Date published
20	Special Report 1966: Construction of an Isthmian Sea-Level Canal by Nuclear Methods: Route 8, Nicaragua-Costa Rica (Revised)	Mar 67
21	Nuclear Excavation Design (Preliminary): Route 17	Mar 67
22	Nuclear Excavation Design (Preliminary): Route 25	Mar 67
23	Summary Report: Construction of an Isthmian Sea-Level Canal by Nuclear Methods: Route 8, Nicaragua-Costa Rica	Mar 67
24	Nuclear Excavation Design (Preliminary): Route 17	Jun 67
25	Nuclear Excavation Design (Preliminary): Route 17	Dec 67
26	Nuclear Excavation Design (Preliminary): Route 25	Dec 67
27	Analysis of Array Concepts for Nuclear Excavation of the Chucunaque Valley Shales, Route 17A	May 68
28	Elements of Emplacement Construction Design for an Isthmian Sea Level Canal	Aug 69
29	Topographic Analysis of Route 25	Sep 69
30	Topographic Analysis of Route 17	Sep 69
31	Summary of Geology and Rock Physical Properties: Route 17	Sep 69
32	Slaking Behavior of the Choco Volcanics	Apr 70
33	Summary of Geology and Rock Physical Properties: Route 25	Oct 69
34	Slope Stability in the Choco Volcanics	Oct 70
35	Engineering Properties of Craters and Principles of Crater Stability	Dec 70
36	Liquefaction Potential of Atrato Valley Soils: Route 25	Aug 70

4. PNE Reports

PNE	Subject	Date published
234F SEDAN	Stability of Crater Slopes	Mar 64
300P Pre-BUGGY	Scope of Chemical Explosive Cratering Experiments	Aug 63
301F Pre-BUGGY	Venting Measurements	Aug 64
302 Pre-BUGGY	Emplacement and Firing of High-Explosive Charges and Crater Measurements	Feb 65
304 Pre-BUGGY	Base Surge Analysis	Sep 63
315F Pre-BUGGY II	Studies of Pre-BUGGY II Apparent Craters	Jun 65
322 BUGGY	Preshot Geologic and Engineering Properties Investigations	Apr 69
501F Pre-SCHOONER	Stem Design and Shotcrete, Grout and Concrete Support	Nov 64
502F Pre-SCHOONER	Crater Measurements	Mar 65
503F Pre-SCHOONER	Base Surge and Cloud Formation	Apr 65

PNE	Subject	Date published
504F Pre-SCHOONER	Strong Motion Seismic Measurements	Sep 65
505P Pre-SCHOONER	Preshot Investigations for Project Pre-SCHOONER, Buckboard Mesa, Nevada Test Site	Sep 65
505F Pre-SCHOONER	Geologic and Engineering Properties Investigations	Mar 67
506F Pre-SCHOONER	Surface Motion Measurements	Oct 68
507 Pre-SCHOONER II	Technical Director's Summary Report	Dec 65
508 Pre-SCHOONER II	Apparent Crater Studies	Nov 66
509 Pre-SCHOONER II	Preshot Geologic and Engineering Properties Investigations	Oct 67
510 Pre-SCHOONER II	Design, Construction, and Postshot Evaluation of Concrete Stem for Access Hole	May 67
511 Pre-SCHOONER II	Cloud Development Studies	Feb 66
512F Pre-SCHOONER II	Airblast Measurements	Sep 67
513 Pre-SCHOONER II	Surface Motion Measurements	May 68
514 Pre-SCHOONER II	Ground Shock Measurements	Apr 66
515 Pre-SCHOONER II	Subsurface Effects Measurements	Jan 66
516 Pre-SCHOONER II	Postshot Geologic and Engineering Properties Investigations	Sep 67
527 SCHOONER	Far-Out Fallout Collection Program for Project SCHOONER	Jun 70
601F DUGOUT	Apparent Crater Studies	Mar 65
602F DUGOUT	Geologic and Engineering Properties Investigations	Dec 67
609F DUGOUT	Deep Underground Shock Measurements	Dec 64
610F DUGOUT	Concrete, Grout, and Shotcrete Support, and Design and Postshot Evaluation of Stem	Dec 64
713F SULKY	Crater Measurements	Oct 65
719P SULKY	Preshot Geologic Investigations	Mar 65
720 SULKY	Geologic and Engineering Properties Investigations	Sep 66
904F PALANQUIN	Studies of the Apparent Crater	Apr 66
905F PALANQUIN	Preshot Geologic and Engineering Properties Investigations	Jun 67
957 CABRIOLET	Engineering Properties Investigations of the CABRIOLET Crater	Oct 69
966 CABRIOLET	Preshot Geological Engineering Investigations for Project CABRIOLET, Pahute Mesa, Nevada Test Site	Jun 67

PNE	Subject	Date published
1100 Pre-GONDOLA	Seismic Site Calibration	May 68
1101 Pre-GONDOLA	Site Selection Investigations	Feb 67
1102 Pre-GONDOLA	Technical Director's Summary Report	May 68
1103 Pre-GONDOLA	Geologic Engineering Investigations and Properties of Craters	May 69
1104 Pre-GONDOLA	Close-in Ground Motion, Earth Stress, and Pore Pressure Measurements	Sep 67
1105 Pre-GONDOLA I	Intermediate Range Ground Motion	Jul 67
1106 Pre-GONDOLA I	Structures Instrumentation	Aug 67
1107 Pre-GONDOLA I Part I	Crater Studies: Crater Measurements	Dec 67
1107 Pre-GONDOLA I Part II	Crater Studies: Surface Motion	Feb 69
1108 Pre-GONDOLA I	Cloud Development Studies	Sep 67
1110 Pre-GONDOLA I	Lidar Observations of Pre-GONDOLA I Clouds	Jul 67
1111 Pre-GONDOLA I	Preshot Geophysical Measurements	Jul 67
1112 Pre-GONDOLA II	Summary Report	Feb 71
1113 Pre-GONDOLA II	Close-in Ground Motion and Earth Stress	Oct 68
1114 Pre-GONDOLA III	Summary	Apr 70
1115* Pre-GONDOLA II	Intermediate Range Ground Motions for Pre-GONDOLA II and Associated Events	Oct 68
1116 Pre-GONDOLA II	Structures Instrumentation	May 68
1117 Pre-GONDOLA III Phase II	Summary Report: Connecting Row Charge	Sep 70
1118 Pre-GONDOLA III	Microbarograph Measurements	Jun 71
1119 Pre-GONDOLA II	Airborne Lidar Observations	Nov 67
1120† Pre-GONDOLA III	Connection of a Row Crater to a Reservoir	Aug 71
2000 ICS-1964	Isthmian Canal Plans—1964 Annex C, Appendix 1, Nuclear Excavation Plan	Sep 64
2001 ICS-1964	Isthmian Canal Studies—1964: Inclosure A, Excavation with Nuclear Explosions	Sep 64

*Published also as UCRL-50433.

†Published also as TR-38.

PNE	Subject	Date published
5001P GEOLOGY	Engineering Geology of Buckboard Mesa, Nevada Test Site	Jul 64
5003 FEASIBILITY APPLICATIONS	Investigation of Manufacture of Aggregate and Riprap by Nuclear Means	Feb 65
5004F FEASIBILITY/ CONSTRUCTION TECHNIQUES	Construction Techniques and Costs for Underground Emplacement of Nuclear Explosives	Apr 69
5005 DANNY BOY	Engineering Geologic Investigations	Aug 66
5006 FEASIBILITY/ SAFETY	Trace Elements in Common Rock Types and their Relative Importance in Neutron-Induced Radioactivity Calculations	Jun 66
5008 FEASIBILITY/ SAFETY	Distribution of Selected Trace Elements in Rocks	Feb 68
5009 CRATER STABILITY	Engineering Properties of Nuclear Craters: Report 4, The Formation and Stability of Slopes in Cohesionless Materials	Aug 67
5010 CRATER STABILITY	Engineering Properties of Nuclear Craters: A Study of Selected Rock Excavations as Related to Large Nuclear Craters	Sep 67
5011 ZULU II	The Formation of a Crater as Observed in a Series of Laboratory-Scale Cratering Experiments	Sep 67
5012-I CRATER STABILITY	Engineering Properties of Craters: Description of Crater Zones and Site Investigation Methods	Feb 68
5013	Crater Stability Under the Influence of Large Seismic Motions	Mar 71

5. Miscellaneous Reports

	Subject	Date published
EERC-69-16	The Behavior of Sands under Seismic Loading Conditions	Dec 69
WES MP S-68-3	Application of Finite Element Method in Determining Stability of Cratered Slopes	May 68
WES MP S-68-8	Selected Methods for Analyzing the Stability of Crater Slopes	Jul 68
WES MP H-69-5	Hydraulic Characteristics of Nuclear Excavated Channels	May 69
WES MP H-69-6	Canal Density Currents	May 69
WES MP S-69-12	Variation in Angle of Internal Friction with Confining Pressure	Apr 69
WES MP S72-2	Application of Finite Element Method in Determining Stability of Crater Slopes	Jan 72
WES MP 3-895	Preshot Geological and Engineering Conditions at the Project FLIVVER Site, Nevada Test Site	May 67
WES MP 3-902	Chukar Mesa Investigation: Exploration of Areas for a Possible Hard-Rock Cratering Site—BUGGY I	Jun 67
WES MP 3-974	Settlement of Fallback Materials	Feb 68

	Subject	Date published
WES MP 3-981	Survey of Slope Failures in Reservoirs	May 68
WES TE-72-2	Seepage and Groundwater Effects Associated with Explosive Cratering	Apr 72
WES TR-3-699 (Rpt. 1)	Site Selection Investigations, Wet Medium Cratering Experiments	Oct 65
WES TR-3-699 (Rpt. 2)	Theoretical Studies of Cratering Mechanisms Affecting the Stability of Cratered Slopes—Phase II	Oct 65
WES TR-3-699 (RPT. 3)	Review and Analysis of Available Information on Slopes Excavated in Weak Shales	Aug 65
WES TR-3-699 (Rpt. 5)	Residual Shear Strength of Weak Shales	Dec 66
WES TR-3-699 (Rpt. 6)	Theoretical Studies of Cratering Mechanisms Affecting the Stability of Cratered Slopes—Phase III	Mar 67

6. Articles

	Subject	Date published
Article 1	Trace Elements in Common Rock Types and Their Relative Importance in Neutron-Induced Radioactivity Calculations	1968
Article 2	Nuclear Excavation Design of a Transisthmian Sea-Level Canal	Sep 69
Article 3	The Corps of Engineers Nuclear Construction Research Program	Sep 69
Article 4	Formation and Engineering Characteristics of Nuclear Craters for Construction Purposes	Jun 68
Article 5	Nuclear Excavation Research	Sep 68
Article 6	The Corps of Engineers Nuclear Construction Research Program	1970
Article 7	A Concept of Row Crater Enhancement	1970
Article 8	Status of the Interoceanic Canal Study	Jan 70
Article 9	Excavation Research with Chemical Explosives	Jan 70
Article 10	Prediction of Gamma Exposure Rates in Large Nuclear Craters	Jan 70
Article 11	Stability of Nuclear Crater Slopes in Rock	Jan 70
Article 12	A Simple Technique to Determine the Size Distribution of Nuclear Crater Fallback and Ejecta	Jan 70
Article 13	Use of Nuclear and Conventional Explosives in Construction	Oct 70
Article 14	Project Pre-GONDOLA: Explosive Excavation Experiments in Clay Shale	Mar 70

	Subject	Date published
Article 15	The Corps of Engineers Nuclear Construction Research Activities	Jan 70
Article 16	A Demonstration Project in the Explosive Excavation of a Railroad Cut	Apr 71
Article 17	Explosive Excavation Current Trends	May 71
Article 18	Slope Analysis for Explosive Excavations	Sep 71
Article 19	Explosive Excavation	Sep 71
Article 20	Large Yield Explosive Charges and Effects	Sep 71
Article 21	Low Cost Excavation with Large Explosives	Sep 71
Article 22	Explosive Excavation Research: Projects TUGBOAT and TRINIDAD	Oct 71
Article 23	Simulating Subsurface Nuclear Explosions with Chemical Explosives	Oct 71
Article 24	Rapid Excavation with Explosives	Apr 71
Article 25	The Corps is Putting Explosive Excavation Design on a More Scientific Basis	Feb 72
Article 26	Progressive Failure Model for Clay Shale	Mar 72
Article 27	Army Develops "Instant Excavation"	Apr 72
Article 28	Explosive Excavation Development for Construction and Combat Applications	Apr 72
Article 29	Explosive Excavation Research	Apr 72

B. NCG/EERL Technical Report Abstracts

(Listed sequentially by report number)

TR-1 (DASA 1669) June 1966

MILITARY ENGINEERING WITH NUCLEAR EXPLOSIVES

Kurtz, M. K., and B. C. Hughes

The manual contains technical information concerning cratering with nuclear explosives and the associated hazards. It also describes techniques for using nuclear explosives to accomplish practical military engineering tasks.

The technical information includes: (1) characteristics of nuclear explosives; (2) mechanics of crater formation; (3) apparent crater dimensions for various media determined by experiments with single and row charges; (4) characteristics and engineering properties of true and apparent craters; and (5) emplacement construction and stemming.

The safety of any particular application may be assessed using the information presented on the hazards of radioactivity, ground shock, air blast, thermal radiation, and missiles from nuclear cratering detonations. Appendices contain procedures and methods for both tactical and detailed fallout prediction.

The techniques for military engineering employment of nuclear explosives are given, showing: (1) demolition of hard targets such as bridges, dams, airfields, and tunnels; (2) the creation of terrain barriers through demolition of fills and cuts or blocking defiles with landslides; and (3) application of nuclear explosives as a tool for military construction of navigable channels and beach landing facilities by means of nuclear excavation.

This engineering manual supplements other publications which describe the tactical aspects of employment of nuclear explosives.

TR-2 September 1968

NUCLEAR CONSTRUCTION ENGINEERING TECHNOLOGY

Hughes, B.C., Holmes, R.S., Redpath, B.B., Andrews, J.B., Day, W.C., Fisher, P.R., Bechtell, W.R.

This report provides the technology which enables the engineer to make engineering, safety and cost analysis of the applicability and feasibility of using nuclear explosives in conjunction with the construction of specific civil works projects.

A discussion of the basic concept of using nuclear explosives for construction purposes and a description of the types of projects which appear to have the greatest potential as nuclear construction applications is presented. An explanation of the elements which must be considered in assessing the engineering feasibility of using nuclear construction methods is included together with a recommended procedure which may be used in accomplishing the design. Data are presented pertaining to the phenomenology of nuclear crater formation as well as information concerning the techniques currently available for predicting the engineering characteristics of nuclear craters and evaluating, in turn, the potential long-term engineering behavior of nuclear excavations. Technical data pertaining to the safety considerations of the radioactivity release, seismic propagation and airblast which accompany a subsurface nuclear detonation and methods for assessing the impact that these phenomena will have on project feasibility are also presented.

Engineering criteria which may be used in the design of specific nuclear construction projects and information concerning the conventional construction requirements which must be accomplished in conjunction with nuclear excavations are presented. The scope of nuclear field operations which must be accomplished in order to emplace and detonate nuclear explosives in a manner that will insure public safety is discussed. A discussion of the items which must be considered in estimating the overall cost of a nuclear construction project and quantitative cost estimating data for use in evaluating the economic feasibility of a given project is presented. A typical detailed nuclear construction feasibility study is presented. This study illustrates the manner in which the technical data provided in this report may be used. Guidelines for accomplishing the design of a nuclear construction project are also offered.

TR-3 November 1968

PROJECT ZULU II, PHASE I: SINGLE-CHARGE CALIBRATION SERIES

Johnson, W. W. and Nelson, D. L.

Phase I of Project ZULU II was a laboratory-scale crater modeling experimental series consisting of the detonation of forty-two 1-lb C-4 charges in a moist compacted sand. This experimental series was conducted by the U. S. Army Engineer Nuclear Cratering Group (NCG) at the University of California Lawrence Livermore Laboratory's (LLL) High Explosive Test Facility, Site 300, near Livermore, California.

The primary objectives of Phase I of Project ZULU II were: (1) to calibrate the medium with respect to its cratering characteristics; (2) to determine the reproducibility of the crater dimensions; (3) to conduct surface motion studies; and (4) to study ejecta and fallback distribution as well as the nature of the displacements occurring in the near vicinity of the zero point and the rupture zone.

The cratering curves developed from these experimental series showed an optimum depth of burst (DOB) of 1.5 ft and a rapid decrease of apparent crater dimensions until no crater resulted at a DOB greater than approximately 2.1 ft. The data for ten charges detonated at a nominal DOB of 2 ft resulted in a fractional standard deviation of 6.4% for crater radius and 20.6% for crater depth, the largest deviations observed for any DOB. The detonation of additional 1/2-lb and 2-lb C-4 single charges showed that cube-root scaling of apparent crater dimensions was applicable at these yields.

The maximum surface ground zero (SGZ) vertical target velocity, V_{SGZ}, was observed to a function of DOB and conformed to the relationship $V_{SGZ} = 470/DOB^{3.1}$. The resultant velocity, V, of a surface target can be described in terms of DOB and the cosine of the angle between the vertical and a line drawn through the surface target and the shot point, θ_r. This equation can be expressed as:

$$V = \frac{470 \cos_r^{3.6}}{DOB^{3.1}}$$

The ejecta pellet studies did not successfully record pre- and postshot locations of the material actually ejected from the crater. It was indicated that the fallback was composed of material originating from over the zero point and in the region near the apparent crater boundary.

TR-4 (Secret) December 1969

REPORT OF FAROUT FALLOUT COLLECTION FOR PROJECTS CABRIOLET AND BUGGY

Andrews, J. B., Gibson, T. A., Jr., Sato, E. S

Sampling programs were undertaken to collect fallout debris of large distances downward from the CABRIOLET and BUGGY nuclear cratering events. Fallout collectors were placed at three predetermined distances along three arcs just before cloud

arrival and retrieved shortly after cloud passage. The collectors were later analyzed to determine the species and quantities of radionuclides present on the collector.

These analyses indicate ground deposition at various downwind locations. Experimental measurements are compared to two different predictive methods for estimating long-range fallout deposition.

TR-5 November 1968

PROJECT ZULU II: LABORATORY-SCALE ROW-CHARGE CRATERING STUDIES

Novak, M. A.

Sixteen row-charge cratering experiments using 1-lb charges of C-4 were conducted by the U. S. Army Nuclear Cratering Group at the University of California Lawrence Livermore Laboratory's Site 300. The cratering medium used for these experiments was a carefully controlled, moist, compacted sand. The purpose of these experiments was to investigate the formation phenomenology and crater geometry of a single row of explosive charges. The spacing between individual charges within the row, the depth of burst of the charges, and the row-connection designs were varied to evaluate the effect of these parameters on the resulting row crater configuration.

Row-charge depths of burst (DOB) varied from 1.75 to 2.50 ft and charge spacings varied from 0.7 to 1.2 R_a. The enhancement of row crater dimensions (width and depth) compared to single-charge craters at equivalent depths of burst decreased as charge spacing increased and as DOB decreased. Single-charge dimensions were approached at spacings greater than 1.2 R_a. At DOB's near optimum (i.e., 1.75 ft), the minimum ratio of lip crest height to apparent crater depth, H_{al}/D_a, was approximately 0.35 and the minimum ratio of width of apparent lip crest to width of apparent crater, W_{al}/W_a, was approximately 1.4.

The maximum surface ground zero (SGZ) target velocity varied with DOB according to the relationship, $V_{SGZ} = 310\ (DOB)^{-2.5}$. In general, the crater volume per charge was maximized at a charge spacing of 1.1 R_a.

The smoothest row-charge connection was obtained for that experiment in which the ratio of the distance from connecting charge to nearest free surface to the DOB of the connecting charge (NFS/DOB) was approximately 0.80, the most irregular row-charge connection was obtained when this ratio was approximately 0.92.

TR-6 October 1968

NUCLEAR EXCAVATION DESIGN OF A TRANSISTHMIAN SEA-LEVEL CANAL

Hughes, B. C.

This paper presents an up-to-date analysis of the application of nuclear excavation technology to the design of a sea-level canal connecting the Atlantic and Pacific

Oceans. This analysis is based on the technical data obtained to date under the auspices of the Atlantic-Pacific Interoceanic Canal Study Commission (A-PIOCS) which was appointed by the President of the United States in April 1965 to make a full and complete investigation and study of the feasibility of, and most suitable route for, constructing a sea-level canal connecting the Atlantic and Pacific Oceans. The scope of this study effort, which is currently in progress, also includes consideration of the best means of constructing a transisthmian canal, whether by conventional or nuclear excavation methods, and determination of the total estimated cost of construction. Consideration is given in this paper to the use of nuclear methods in the construction of a sea-level canal through the Darien region of Panama (Route 17) and the Atrato-Truando region of northwest Columbia (Route 25).

The site data required for a comprehensive nuclear excavation design analysis of the proposed sea-level alignment include information pertaining to site topography, geology, hydrography, hydrology, meteorology, seismic propagation characteristics, bio-environmental conditions and medico-ecology. These site data are used, together with data pertaining to nuclear explosive characteristics, cratering characteristics of pertinent geologic media, nuclear cratering detonation effects and channel design criteria, to develop an engineering-safety-cost analysis which is the basis for the nuclear excavation design.

The results of geologic investigations to date along the 46-mi Route 17 alignment indicate that approximately 20 mi of the alignment through the Chucunaque Valley encounters a weak, saturated clay shale material while the balance of the excavation would be through relatively competent rock media. In view of the unfavorable long-term slope stability characteristics of the Chucunaque Valley clay shales, it has become necessary to develop techniques for using nuclear explosives to produce linear craters that have initially flat slopes of the order of 7 to 9°. Experimental evidence to date indicates that nuclear excavation using a two-pass, triple-row array detonation system may offer a solution to the problem of obtaining flat slopes in the Chucunaque Valley clay shales.

A preliminary analysis of the topography and geology along the Route 25 sea-level canal alignment through northwest Colombia indicates that conventional excavation techniques, primarily hydraulic dredging, would be the most reasonable method of excavating approximately 78 mi of the 100-mi alignment. The remaining 23 mi of the alignment, through the Continental Divide, would be excavated using nuclear explosives.

Studies are currently in progress pertaining to the safety aspects of using nuclear methods to construct a transisthmian sea-level canal to include consideration of seismic propagation, airblast acoustical wave phenomena and radioactivity release. The results of these studies to date indicate that the potentially damaging effect on buildings of the ground motions resulting from seismic propagations from the nuclear detonations will be the major factor in determining the maximum aggregate yield that can be detonated at any one time along the selected alignment.

TR-7 (Not used)

TR-8 October 1968

THE CORPS OF ENGINEERS NUCLEAR EXPLOSIVES STUDIES FOR CIVIL CONSTRUCTION

Hughes, B. C.

This report discussed the major activities being undertaken under the Corps of Engineers research program pertaining to nuclear explosives studies for civil construction. This program, which was initiated in 1962, supports the joint Corps of Engineers-Atomic Energy Commission research program to develop the technology required to use nuclear explosives in conjunction with the construction of large-scale civil projects. The U. S. Army Engineer Nuclear Cratering Group (NCG), located at the Lawrence Livermore Laboratory (LLL) in Livermore, California, is responsible for the technical direction and execution of this Corps of Engineers' research and development effort.

The primary NCG program activities include: (1) execution of High Explosive (HE) cratering experiments to develop cratering characteristics data for geologic media of interest and serve as calibration experiments for large-scale nuclear experiments; (2) participation in and joint planning of AEC nuclear excavation experiments; (3) development of pertinent data on the engineering characteristics and physical properties of nuclear craters; (4) development of civil works nuclear construction technology; (5) accomplishment of engineering studies to identify and solve engineering and construction problems involved in the use of nuclear explosives in construction of Civil Works projects; and (6) execution of joint CE/AEC Civil Works nuclear construction experiments.

NCG has executed five major HE cratering experiments to date. These experiments have provided significant empirical data for use in the design of nuclear excavation experiments as well as in the development of cratering code calculation techniques.

The results of the NCG engineering feasibility studies program to date have indicated that the following four nuclear civil construction applications have significant potential for accomplishment: (1) nuclear quarrying to produce rockfill or aggregate; (2) nuclear ejecta dam construction; (3) nuclear harbor construction; and (4) nuclear canal excavation. The nuclear quarry concept has been identified as the most immediate application of present technology.

TR-9 (Not used)

TR-10 March 1969

CONSTRUCTION TECHNIQUES AND COSTS FOR EMPLACEMENT OF NUCLEAR EXPLOSIVES IN DISTURBED MEDIA

Hair, J. L.

This report describes state-of-the-art methods and preliminary cost estimating procedures considered applicable to nuclear explosive emplacement construction through disturbed zones associated with single, row, and array craters produced by

nuclear explosives. These shafts would be used primarily for connecting row craters and for emplacement of additional devices to modify the geometry of existing craters. A secondary purpose would be to provide access to previously buried but undetonated devices. Civil works projects presently being considered for construction by nuclear methods include: (1) dam construction, (2) canal excavation, (3) harbor construction, and (4) quarrying operations.

Cratering studies conducted by the Nuclear Cratering Group in hard rock, clay shales, and cohesionless, granular materials such as desert alluvium show that the areas of disturbance in and around a crater formed by nuclear detonation may be categorized into zones according to their physical characteristics. In crater terminology these are defined as the ejecta, fallback, and rupture zones.

Recorded data of actual reentry into these zones are very limited. Most of the available information that directly relates to crater excavations generally pertains to small-diameter holes (6 in. and less) which have been rotary drilled. Techniques utilized for these investigations, together with those documented for drilling in glacial till, offshore drilling of unconsolidated sediments, and conventional shafting of "bad ground," have been evaluated in the preparation of this report.

Many techniques and/or combination of techniques using a multiple of equipment types were studied. Of these, the most applicable for excavation of shafts through crater zones appears to be variations of "big hole" rotary drilling and conventional mining. A description of these methods and the necessary equipment for their employment are listed in the text.

Cost analysis for excavating large-diameter bores through disturbed media zones in and near existing craters is extremely difficult. Various companies and individuals connected with the drilling and mining industry were surveyed in an attempt to arrive at some reasonable method for cost prediction. The cost information contained in this report should be considered for preliminary planning only.

TR-11 (FOUO) May 1970

NUCLEAR EXPLOSIVE QUARRYING POTENTIAL WITHIN NORTH PACIFIC ENGINEER DIVISION

Eccles, H. L. and Kleist, E. H.

This report presents a study of the long-range potential for using nuclear quarrying in the Pacific Northwest and Alaska, and provides an estimate of the minimum rock requirement for which nuclear quarrying techniques should be considered.

Twenty projects under consideration by the Corps of Engineers, Bureau of Reclamation, State and quasi-governmental agencies were evaluated for use of nuclear quarrying techniques. The engineering, safety and economic aspects of using nuclear quarrying on eight of the projects are included in the report. Because construction planning had not been initiated for any of the projects, the quarry sites were selected

on the basis of information contained in literature, existing topographic and geologic maps, and in most cases, a brief surface reconnaissance.

The report recognizes that certain assumptions for the study should be verified by full-scale tests prior to using nuclear quarrying in construction operations. The concept of nuclear quarrying is considered sound, however, and the study indicates that nuclear quarrying offers economical savings for four of the eight projects. A fifth would be included if the nuclear quarry could be located within an appropriate haul distance of the dam site. Nuclear quarrying would be as economical as conventional quarrying for a sixth project. The remaining two projects are too small to economically justify use of nuclear quarrying techniques. In general, nuclear quarrying should be considered when quarry requirements exceed 5 million in situ yd^3 for a concrete project or 6.8 million in situ yd^3 for a rockfill project.

TR-12 June 1969

CONVENTIONAL EXCAVATION METHODS AND COSTS FOR USE IN FEASIBILITY STUDIES OF NUCLEAR AND CONVENTIONAL EARTHWORK PROJECTS

Wills, J. D. and Brunken, C. O.

Modern earthmoving projects require that close consideration be given to the planning and engineering of equipment systems. Although the use of nuclear explosives offers a new approach to moving huge quantities of material, conventional equipment would still be required for a substantial portion of the work. The purpose of this report is to provide information on current methods and costs of using conventional earthmoving equipment in conjunction with projects excavated by nuclear explosives. However, the information is applicable to any large scale excavation project.

The initial sections of the report present introductory material and the basic fundamentals of estimating the costs for earthwork excavation. Section 6 discusses the principles of selecting an equipment system. The remaining sections discuss the major items of equipment which might be used on a major earthwork project. The Appendices contain references, supplemental information on price adjustment factors and illustrative problems.

TR-13 December 1970

QUARRYING WITH NUCLEAR EXPLOSIVES

Vesic, Aleksandar S.

Studies of the phenomenology of crater formation have been conducted at Duke University for many years with emphasis on the problems of large-scale excavation. This report reviews the findings of those studies, but with emphasis on their relevance to the concept of quarrying with large-yield explosions at relatively deep depths of burst. Some simple rules are established for the correlation of small-scale events under sloped terrain to analogous events under level terrain. Analyses are made of

known cratering experiments in basalt and granite using the author's "incremental" approach as opposed to the conventional "scaled depth" approach. The results of these analyses are applied to the analysis of a proposed nuclear quarrying event at a hypothetical site in a granitic medium.

TR-14 September 1969

NATURAL RUBBLE SLOPES AND THEIR RELEVANCE TO CRATER FALLBACK SLOPES

Lutton, R. J.

Natural rock rubble deposits offer useful information on characteristics and behavior of crater fallback if their geomorphic histories are recognized and understood.

The characteristics of seven slope deposits were considered: talus, colluvial, mantle, alluvium, mudflow debris, rock glaciers, moraine and modified debris. Of these, talus is most similar to fallback.

Talus slopes range to 1600 ft or greater in height and appear to average about 34, 33, 31, 31 and 24 deg in semiarid, alpine, subarctic, temperate, and tropical climates, respectively. Mixing of materials by a cratering event should tend to make fallback slightly more stable than corresponding natural rubble.

Fallback is out of equilibrium with its environment, particularly the manifestations of climate, and may undergo major erosional and weathering modifications. The long-range result of these modifications, however, is a more stable configuration.

TR-15 Vol 1 December 1970
Vol 2 July 1971

EMPIRICAL STUDY OF BEHAVIOR OF CLAY SHALE SLOPES

Fleming, R. W., Spencer, G. S., and Banks, D. C.

This study was undertaken to determine the factors that lead to instability in clay shale to provide a basis for assessing the probable long-term stability of high crater slopes in clay shales.

The chief features contributing to the engineering behavior of clay shales are degree of overconsolidation and lithology, both of which reflect geologic history. Local geologic structure and hydrologic conditions affect individual slopes. Weak layers may present slope hazards, while conversely a few stronger layers may materially strengthen an entire clay shale slope. Time-dependent phenomena are important in clay shale slopes, which may fail after standing apparently stable for many years.

Intensive studies were conducted of natural slopes in five clay shale units in the upper Missouri Basin. The Claggett, Bearpaw, and Pierre formations, all marine-deposited shales of Late Cretaceous age, showed extensive slope failures; high slopes generally stood at overall inclinations of only 5 to 10 deg, which are comparable to the residual angles of internal friction of the materials. The Cretaceous Colorado group

and Lower Tertiary Fort Union group showed steeper slopes with fewer failures. Intensive laboratory testing of physical properties of all materials indicated that only gross differences in slope behavior can be related to any specific test or series of tests.

Engineering practice in clay shale materials is customarily based on an empirical approach, attention being given to local site conditions and to the observed behavior of existing nearby slopes. Limited observations of experimental crater slopes in clay shale are available. The conclusion is reached that future design crater slopes must be based on experiences with conventionally excavated slopes. Furthermore, the design of cratered slopes must be conservative, although no experience indicates that the slope inclination needs to be as flat as the residual angle of internal friction of the site materials.

TR-17 June 1969

PROJECT TANKTRAP: A FIELD EVALUATION OF NUCLEAR TERRAIN BARRIERS

Hughes, B. C., Harrison, W. L., and Paul, R.

Project TANK TRAP was conducted to determine the capability of selected tactical vehicles to traverse craters typical of those which could be produced with Atomic Demolition Munitions (ADM). The vehicles included in the test program were the M-60 Tank, M-113 Armored Personnel Carrier, and an articulated two-unit general purpose vehicle called the POLECAT. Trafficability testing of these vehicles was performed in the SCOOTER crater, the JANGLE U crater, and Pre-SCHOONER Bravo crater. The results of the research project indicate that: (1) craters formed in dry soil by the detonation of explosives at the surface or at very shallow depths of burst (down to approximately 20 $ft/kt^{1/3.4}$) do not present significant trafficability problems to tracked tactical vehicles; (2) craters formed at or near optimum depth of burst (160 $ft/kt^{1/3.4}$) in dry soil are a trafficability obstacle to tracked tactical vehicles; and (3) craters formed in hard rock, such as basalt, cannot be negotiated by tracked tactical vehicles without major modification of the crater and/or assistance by heavy duty equipment, either mobile or fixed.

TR-18 March 1970

A SIMPLE TECHNIQUE TO DETERMINE THE SIZE DISTRIBUTION OF CRATER FALLBACK AND EJECTA

Anderson, B. D., II

Particle size distributions of fallback and ejecta have been determined principally by mechanical sieving and weighing. However, as the size of nuclear craters produced in the experimental program increased, it became increasingly more expensive to

continue this procedure, particularly since the reliability of the data is proportional to the fraction of total available material investigated.

An alternate technique to sieving and weighing involves the selection and measurement of particles lying beneath points along a selected line of traverse. A pebble count technique originated by Wolman (1954) has been modified and given theoretical justification (Delesse Relation) for generating a cumulative curve interpretable as a size-weight distribution. Data gathered to date indicate the results obtained are comparable to sieving and weighing the same material.

Application of the technique to the DANNY BOY, CABRIOLET, BUGGY and Pre-SCHOONER Alpha, Bravo and Charlie crater ejecta indicates the method can be successfully applied to both nuclear and chemical explosive crater fallback and ejecta.

TR-19 January 1970

THE NCG FALLOUT SCALING MODEL: A GRAPHIC-NUMERICAL METHOD OF PREDICTING FALLOUT PATTERNS FOR NUCLEAR CRATERING DETONATIONS

Burton, D. E.

A scaling model is developed to predict the H + 1 hr exposure rate in the area contaminated by the radioactive fallout from an underground nuclear detonation fired at any depth of burst. Exposure rate predictions can be made within the base surge region in both the upwind and crosswind directions and in the downwind fallout pattern to a distance at which the 0.01 R/hr exposure contour would be experienced. These predictions can then be used to construct isoexposure-rate contour maps for feasibility studies. The model is developed by requiring the observed and predicted exposure rates for seven underground (DANNY BOY, TEAPOT ESS, CABRIOLET, SEDAN, SCHOONER, JANGLE U, and BUGGY) and two surface (JANGLE S and JOHNIE BOY) detonations to be consistent. The results indicate that predictions based on this model will be reliable to within a factor of 2 to 4. A significant result of this investigation was a method of the partitioning of activity between the base surge and the main cloud.

TR-21 June 1971

EXPLOSIVE EXCAVATION TECHNOLOGY

Johnson, S. M., Bourque, R. F., Day, W. C., Gates, R. H., Gilson, D. R., Fraser, R. L., Kleist, E. H., Lattery, J. E., Leahy, E. J., Redpath, B. B., Remboldt, A. L.

This report is the first comprehensive textbook on a relatively new method of construction originating from research into the large-scale use of explosives for construction purposes. The central idea is that explosives can be made to do more work for the civil engineer than just break up rock: various types of excavations and explosion-generated effects can be designed and produced safely, quickly, and in many cases

cheaper than by the use of other techniques. The overall concept, design approach and procedures, and the operational consequences of using currently available techniques are fully described. Emphasis is on the adaptability of the method, and its present and future potential as a cost competitive tool in various construction roles.

The report deals with the mechanism of crater formation and characteristics of explosion-produced craters. It covers the types of projects where such craters have useful application; how to choose the proper explosive; how to design the charge emplacement and firing system; and how to evaluate the potential hazardous effects from detonation. The field operations associated with using the method are described and the postshot engineering considerations are discussed. An example is given illustrating how to analyze a typical excavation project.

Further research needed to increase the adaptability and competitiveness of explosive excavation is presented. Considerable ancillary information for engineers interested in the evolution of explosive excavation, case histories of projects, details relating to explosives and design procedures, and how to contract for explosive excavation services is appended to the report.

TR-22 September 1971

FALLOUT PREDICTION PROCEDURE FOR SUBSURFACE ADM'S

Snell, C. M., Burton, D. E., O'Connor, J. M.

Simplified and detailed methods are presented for predicting exposure rates due to fallout from underground nuclear detonations. The simplified method, which is performed by hand calculations, predicts rough or generalized exposure rate contours in the upwind-crosswind and downwind areas. The detailed method, which can be accomplished by either a hand calculational procedure or a nomogram procedure, predicts generalized exposure rate contours in the upwind-crosswind area and detailed exposure rate contours in the downwind fallout area. All procedures are based on a graphic-numerical scaling model. The quantity predicted by these procedures is the (H+1) hour exposure rate, in R/hr. Time dependent exposure rates, total radiation doses, and the Army-defined hazard zones (Zone I, Ia, and II) boundaries may also be predicted if desired.

The scaling model prediction methods offer the great advantage of predicting exposure rates from the boundary of continuous material ejected by the explosion out to exposure rates on the order of 0.01 R/hr. The methods are valid for detonations at a wide range of depths of burst. Unusual atmospheric or emplacement conditions may reduce the reliability of the results, but approximate techniques are suggested for performing predictions under certain unusual conditions.

TR-23

PROJECT TUGBOAT: EXPLOSIVE EXCAVATION OF A HARBOR IN CORAL — February 1972

Day, W.C., Wnuk, W.J., McAneny, C.C., Sakai, K., Harris, D.L., Berg, D., Kanayama, R., Kawamoto, P., Ballard, R.F., Jr., Marks, R.E., Vortman, L., Nicoletti, J., Keith, J., Mah, B.

A portion of a planned small-boat harbor was explosively excavated in a weak coral material using twelve 10-ton charges of an aluminized ammonium nitrate slurry explosive. This experiment-demonstration executed by the U.S. Army Engineer Nuclear Cratering Group, now designated as the U.S. Army Engineer Waterways Experiment Station Explosive Excavation Research Laboratory (EERL), was code-named Project Tugboat. The charges were emplaced approximately 36 ft deep in the coral reef which was overlain with a water layer averaging approximately 6 ft in depth. Charges were spaced 100 and 120 ft apart. A series of five calibration tests preceded the main harbor detonations. Apparently because of inadequate boostering, two of the main charges did not fully detonate and one charge deflagrated. An additional array of sixteen 1/2-ton charges was subsequently emplaced and detonated to clear that portion of the channel. The detonations resulted in a channel varying in width from about 150 to 260 ft at a minimum project water depth of 12 ft. The berthing basin is almost a square area 400 ft on a side at the 12-ft water depth contour. The explosive craters were broad and shallow with no lips and were actually better suited to harbor excavation than the less wide and deeper craters typical of dry land cratering detonations. The cratering mechanism appears to be one of densification of the coral through crushing and subsequent settling. The crater remains devoid of water for several seconds after detonation and then is filled by coral and water as the crater walls fail into the crater. The extent of the crushing action of the detonations was crudely defined by acoustic profiling surveys.

Several technical programs were conducted including a wave measurement program, a study of the effect of the detonations on the marine environment, a ground-motion measurement program, a structures response study, an airblast measurement program, and a measurement program to determine the peak pressure and the acceleration and velocity of the water directly over the charge positions. Results of all of these programs are included in this report.

TR-25 February 1971

STUDY OF EXPLOSIVES FOR LUNAR APPLICATIONS

Mattes, R. W.

This report describes a preliminary study of the use of chemical high explosives in support of anticipated lunar base activities. The introductory sections present a brief summary of terrestrial chemical high explosives state-of-the-art in the fields of excavation, quarrying, mining, tunneling, shallow-hole drilling and seismic surveying. Explosive excavation is described through discussions of explosive excavation principles, explosives and their properties, methods of charge emplacement and firing, and phenomena and methods of predicting magnitudes of the potentially harmful explosion side effects of ground motion, airblast, and missile (ejecta) throwout.

Based on known and assumed properties of the moon and its environment, a preliminary theoretical study indicates that terrestrial modeling of lunar explosion craters is possible at one-six scale in chambers evacuated to about 30 mm Hg or a full scale by subsequent mathematical adjustment of ejecta ranges, provided an accurate lunar crust model can be constructed. Analyses show that blast waves formed by expanding explosion gases represent no serious hazard in lunar blasting and that missiles (ejecta) will be thrown at least six times farther on the moon as on earth. Current terrestrial ground motion predictive methods are suggested as first approximations to lunar ground motion effects of subsurface explosions. The various elements and suggested techniques of designing lunar explosive excavation projects are discussed. Some applications of explosive excavation techniques are suggested for personnel protection, engineering support of lunar scientific investigations, and lunar base activities. Conceptual designs are presented for six hypothetical applications.

An investigation of the training required for a space crew to perform lunar explosive excavation projects identifies the tasks involved in increasingly complicated projects, examines the background required of a trainee, suggests a course of instruction to prepare space crews for explosive excavation projects of the near future, and assesses Department of the Army capabilities to provide such training.

Areas not fully investigated in this preliminary report are recommended for future research. The recommendations are accompanied by an assessment of the existing capability of Department of the Army agencies to perform the necessary research.

TR-26 (in publication)

CONSTRUCTION OF UNDERGROUND POL STORAGE FACILITIES WITH NUCLEAR EXPLOSIVES

Sprague, K.

This report examines the feasibility of constructing nuclear explosion cavities to be used as hardened storage facilities for petroleum products in a theater of operations.

It is concluded that void volumes of from 50,000 to 250,000 barrels capacity for substitution into the Engineer Functional Components System, could safely and reliably be created at depths of 500 ft/kt$^{1/3}$ with a fission nuclear device of from 1 to 10 kt in yield and emplaced in an 18- to 36-in. diameter, rotary-drilled hole. Stored products could be discharged using submersible turbine pumps, hydraulic displacement, or where terrain allows, gravity flow. Waiting three months after the detonation to inject the petroleum product into the nuclear geostorage container would preclude degradation of critical fuel properties from radiation damage. However, it is not possible to determine the extent of the effects of the thermal, chemical, and physical environment of the chimney on the stored product based on currently available technical information. In order to transform the current state of engineering for nuclear geostorage of petroleum products into usable capabilities which could provide the U.S. Army with the capability of rapidly constructing secure and hardened petroleum storage facilities, experimental evidence is required to demonstrate that the product would be sufficiently free of particulate matter and radioactive contamination and chemical change, such that it might be used for its intended purpose. This demonstration could be conducted by a series of test programs using currently available nuclear chimneys less than one year old. The probability of technical attainability is high because the work involved is an extrapolation of current AEC and Corps of Engineer research efforts in the use of nuclear explosives for construction purposes.

TR-27 September 1970

SEEPAGE CHARACTERISTICS OF EXPLOSIVELY PRODUCED CRATERS IN SOIL AND ROCK

Sherman, W.C. and Banks, D.C.

This report contains a review of the permeability characteristics of soil and rock formations in both disturbed and undisturbed conditions which are likely to occur in the zones surrounding craters. This report presents methods of determining permeability and tabulates typical values of permeability in a variety of materials. Factors which affect the seepage characteristics of craters are discussed, and a few examples are presented to illustrate the influence of seepage on stability calculations.

The data indicate the laminar-flow conditions will prevail in soil and rock formations, dependent upon the size of the pore opening and hydraulic gradient. For a given pore opening, a critical gradient exists above which the flow is found to be turbulent; the technique of constructing flow nets for turbulent flow is illustrated in the report. The correct assessment of seepage conditions in the zones surrounding a crater will depend to a large extent upon the correct evaluation of boundary conditions, such as geological discontinuities and sources of seepage.

TR-28 November 1970

PROJECT TRENCHER: EVALUATION OF ALUMINIZED BLASTING AGENTS FOR CRATERING AND HOLE SPRINGING

Bourque, R. F.

Project TRENCHER* was an explosives evaluation experiment conducted in clay shale at Fort Peck, Montana, by the U. S. Army Engineer Nuclear Cratering Group (NCG). To determine the single-charge cratering performances in clay shale of two aluminized slurry explosives, IRECO DBA22M and Dow MS80-20, 500-lb charges were detonated with a sand-and-water-mixture stemming. Five cratering experiments were conducted with 500-lb charges of DBA22M to determine the effect of different stemming materials on crater volume. Crushed rock, concrete, sand and water, water, and no stemming were the materials used. The test with water stemming gave the largest crater volume. Tests were conducted with 500-lb charges of DBA22M fashioned with length-to-diameter (l/d) ratios of 1 to 9 to determine the effect of different cylindrical charge geometries on crater volume. Charges with l/d ratios between 1 and 4.5 showed a maximum degradation in crater volume of 25% compared to the crater volume obtained with an l/d ratio equal to 1. Hole springing tests with 5- and 10-lb charges of DBA22M placed at depths of 10 to 20 ft demonstrated that each pound of DBA22M placed at a depth of at least 7.0 $ft/lb^{1/3}$ can spring out a volume in clay shale capable of accommodating 200 lb of DBA22M cratering charge

TR-29 January 1971

INITIATION OF FAILURE IN SLOPES IN OVERCONSOLIDATED CLAYS AND CLAY SHALES

Constantopoulos, I. V., Christian, J. T., and Whitman, R. V.

The conditions leading to the initiation of failure in slopes of overconsolidated clay or clay shale are investigated by means of two finite element programs. The analysis is two-dimensional and assumes plane strain in a homogeneous semiinfinite mass. Further, the material is assumed to be linearly elastic and isotropic with body forces. No pore pressure effects are analyzed.

It is shown that there is a considerable difference between the case in which horizontal stresses are induced by horizontal forces exerted far from the slope and the case in which horizontal stresses are "locked in" and released by excavation. The former case is simulated by the code FEAST 1 which has boundary conditions modeling a smooth bottom. The later case is simulated by the code COREXC which is given

*Findings of the Nuclear Cratering Group reported herein do not constitute an endorsement by the Corps of Engineers, U.S. Army, of one manufacturer's product over others of the same type.

boundary conditions modeling a smooth and rough bottom. The smooth bottom models conditions in which relative movement in the horizontal direction is allowed between soil profiles.

The effects of the coefficient of earth pressure (K_0), slope angle (α), and the angle of internal friction (ϕ), are investigated for the two smooth bottom models and the one rough bottom model. The results are presented in the dimensionless ratio $c/\gamma H_0$ where c is the cohesion required to prevent the beginning of failure and γH_0 is the overburden stress at the toe before excavation.

The shear stresses at the toe of the slope for the case where horizontal forces are exerted far from the slope are nearly twice those for the case in which horizontal forces are released by excavation. If horizontal forces are released by excavation, the most stable conditions prevail when the bottom of the layer is rough. In all cases high values of K_0, low values of ϕ, and high values of α lead to the least stable slopes.

TR-30 September 1970

HYDROLOGIC TRANSPORT OF RADIONUCLIDES FROM NUCLEAR CRATERS AND QUARRIES

Kruger, P.

Feasibility studies of proposed applications of nuclear explosions for civil construction have shown that the responsible engineering agency must have the capability to predict the safety of the applications. One specific need for nuclear excavation projects is the development of adequate methods for estimating the hydrologic transport of radionuclides from excavation sites. Such models must consider the complexity of the nuclear, hydrologic, and environmental processes involved and must predict, with reliability, the concentration of radionuclides in surface waters and groundwaters at locations downstream of a nuclear crater or quarry. This report presents a review of the literature related to the development of numerical and experimental methods for predicting the hydrologic transport of radionuclides—with specific application to nuclear excavation and quarrying.

Several models have been developed for predicting surface water and groundwater dispersion and transport of radionuclides. Because of the complexity of the processes involved, major simplifications are required to describe the transport for computer calculation. Since no large-scale excavation or quarrying experiments involving the interaction of water at the detonation site have been conducted, the prediction models have not been confirmed. This report reviews the possibility of using radioactive and activable tracer methods for experimental study of hydrologic transport under field conditions to assist in the development of a successful prediction model.

TR-31 (in publication)

CRATERING IN LAYERED MEDIA

Redpath, B. B.

The effects of a layered medium on cratering phenomena were studied at the Soil Mechanics Laboratory, Department of Civil Engineering, Duke University. The study included 32 small-scale model tests in which the layered medium consisted of a compressible stratum of compacted sand and a stiff stratum of an artificial sandstone. Parameters under study included crater dimensions, subsurface deformation patterns, and surface velocity as functions of charge burial depth and layer configuration.

The tests included half-space and quarter-space models. In the latter, the charge was placed adjacent to a transparent side of the test fixture to permit photography of dynamic phenomena. Spherical 1.68-g charges of lead azide, were used in the half-space tests, and 0.84-g hemispherical charges were used in the quarter-space tests. In most of the tests the stiff stratum was situated below the compressible stratum.

The test results indicated that the existence of layering has considerable influence on cratering phenomena if the interface between the upper and lower strata is nearer to the surface than three times the charge burial depth. For the case where the charge was located in the compressible layer and the compressible layer was on top, craters were found to be deeper, but smaller in diameter, than those formed in a compressible homogeneous medium. Surface velocities were also increased in this case. Initial explosion cavity growth and the final subsurface deformation patterns were also strongly influenced by the relative position of the interface. For the case where the stiff layer is on top and the charge was detonated in the compressible layer, a greater portion of the explosive energy was used to create a charge cavity in the compressible layer, thereby decreasing the maximum charge depth at which breakthrough to the free surface occurs.

TR-32 April 1972

ANNOTATED BIBLIOGRAPHY OF EXPLOSIVE EXCAVATION-RELATED RESEARCH

Mattes, R. W. and Knowles, R. K.

This bibliography contains a description of all reports prepared by, or for, the U. S. Army Engineer Waterways Experiment Station Explosive Excavation Research Laboratory (EERL) and its predecessor, the U. S. Army Engineer Nuclear Cratering Group (NCG) from FY 1964 through FY 1972. The reports address themselves to the many topics associated with the use of chemical and nuclear explosives in excavation projects and each is described by a brief summary or abstract. Indexing is by subject, author, title, and report number.

TR-33 November 1971

PROJECT SERGIUS NARROWS—SUMMARY OF TESTS ON LIESNOI ISLAND, ALASKA, 1970

Gillespie, R. H.

Project SERGIUS NARROWS was executed during the period 8 June through 8 July 1970 in a granitic medium on Liesnoi Island, Alaska. The tests consisted of attempts (1) to spring (enlarge) 57 small-diameter drill holes to accept cratering charges, and (2) to detonate successfully as cratering charges the holes sprung. The tests indicated that hole springing in an intermediate-to-high-strength rock is not economical due to the high probability of hole collapse. The cratering results are sketchy but tend to indicate that the cratering criteria developed for high-strength rock are valid for the granitic medium of Sergius Narrows, Alaska.

TR-34 June 1972

PROJECT TRINIDAD: EXPLOSIVE EXCAVATION TESTS IN SANDSTONE AND SHALE

Redpath, B. B.

A series of single-, row-, and multiple-charge cratering detonations, with individual charge weights of one to two tons, were carried out in weak, interbedded sandstones and shales near Trinidad, Colorado in 1970 and 1971. The principal objectives of these excavation experiments were to obtain single-charge cratering curves, to verify row-charge designs for achieving a specified excavation, to determine the effects of millisecond delays in row-charge cratering, to experiment with cratering in varying terrain, and to compare the cratering effectiveness of several explosives. Three varieties of aluminized ammonium-nitrate blasting agents and ANFO were used. Airblast and seismic effects of each detonation were monitored. The series culminated with the excavation of a 400-ft long railway cut with 44 tons of explosives distributed among 32 charges.

TR-35 June 1971

MIDDLE COURSE I CRATERING SERIES

Fitchett, D. J.

During the period August through November 1970, the U.S. Army Engineer Nuclear Cratering Group conducted Project TRINIDAD, an extensive series of 1-ton single- and row-charge cratering experiments near Trinidad, Colorado. As part of Project TRINIDAD the Defense Atomic Support Agency sponsored the MIDDLE COURSE I series of four surface and two optimum depth cratering experiments. The cratering results of the DASA MIDDLE COURSE I series combined with the results of the Project TRINIDAD tests provided the complete cratering curve for sandstone media. Optimum

depth of burial (dob) was determined as 130 ft/kt$^{0.3}$. Scaled crater radius (r_a) and depth (d_a) at optimum dob were 167 ft/kt$^{0.3}$ and 94 ft/kt$^{0.3}$, respectively. Crater dimensions for stemmed and unstemmed detonations at optimum dob differed by 10 to 15%, the stemmed crater sizes being the larger.

TR-36 July 1971

ANALYTICAL AND GRAPHICAL METHODS FOR THE ANALYSIS OF SLOPES IN ROCK MASSES

Hendron, A. J. Jr., Cording, E. J., Aiyer, A. K.

In this report the methods of analyzing the static stability of rock slopes cut by a three dimensional network of discontinuities are given. The general use of vector analysis to solve these problems analytically is described and a method utilizing stereonets to solve these problems graphically is also given. For both the graphical and analytical methods the general analysis of slopes cut by one, two, or three sets of discontinuities is presented which can take into account the porepressures acting on the discontinuities and external forces acting on the slope. Detailed examples are given to illustrate both the graphical and vector methods of analysis.

The dynamic stability of slopes is also treated in this report. It is shown that the dynamic resistance of a three-dimensional rock slope can be calculated by either the graphic-stereonet method or the analytic vector analysis method. The dynamic resistance can then be used to estimate the movement of the slope under dynamic loading using a procedure given by Newmark (1965). A criterion is then given for determining if the calculated movement of the rock slope is acceptable or harmful.

TR-37 May 1971

SUMMARY OF TIME-DELAYED ROW-CHARGE CRATERING EXPERIMENTS, SITE 300, 1970

Meisinger, R. J.

The time-delayed row-charge cratering program was conducted at Lawrence Livermore Laboratory's High Explosive Test Facility (Site 300) by the U. S. Army Engineer Nuclear Cratering Group (NCG) to evaluate the effect on cratering performance of time delays between successive charges in single row-charge detonations and time delays between rows in double row-charge detonations. Tests were conducted using 1- and 2-lb charges of composition C-4 explosive in sand.

Maximum crater volume for the single row-charge configuration occurred with the simultaneous detonation of all charges. As time delays between successive charges were increased from 0 to 100 msec, total crater volume decreased by 36%.

The total cross-sectional area of the crater from a double row-charge detonation in level terrain remained approximately constant for delay intervals from 0 to 100 msec

between rows. That portion of the area between the charges of adjacent rows increased 62% as the delay interval increased from 0 to 100 msec.

The total cross-sectional area and that portion of the area between the charges of adjacent rows of the crater from a double row-charge detonation on an 8-deg side slope were greater when fired with a 50-msec delay between rows as compared to simultaneous detonation.

TR-38 August 1971

PROJECT PRE-GONDOLA III PHASE III: CONNECTION OF A ROW CRATER TO A RESERVOIR

Redpath, B. B.

Project Pre-GONDOLA III Phase III, the connection of a row crater to a reservoir, was executed on 6 October 1969 and was the culmination of several years of cratering experiments in saturated clay shale near Fort Peck, Montana. This experiment used a total of 70 tons of an aluminized ammonium nitrate blasting agent in a row of five charges to remove a barrier between an existing row crater and the Fort Peck Reservoir. The excavation produced by the detonation had a volume of about 63,000 yd^3. The blasting agent appears to have a cratering effectiveness approximately 1.6 times that of TNT.

TR-39 November 1971

A REVISED EMPIRICAL APPROACH TO AIRBLAST PREDICTION

Snell, C. M. and Oltmans, D. L.

Airblast from buried chemical and nuclear detonations has been under systematic investigation for two decades. There now exists a sizable body of information collected during field experiments conducted over the years. The report contains a summary compilation of the available data for all significant large-yield events and synthesizes this data into an empirical prediction method.

Since the airblast from buried detonations approaches a consistent attenuation at the longer ranges of interest for safety predictions, a purely empirical "transmission factor" analysis based on consistent longer range data from subsurface detonations is used. Transmission factors are established as functions of scaled depth of burst for a variety of media and types of explosives. These are used to predict both ground-shock and gas-vent airblast from single- and row-charge detonations. A new approach to predicting the close range overpressures is also discussed. A summary of airblast from surface bursts is included.

The empirical prediction method presented is well founded for those types of events which have been extensively investigated. Its chief weakness lies in the prediction of dissimilar events (different yields, explosive types, or media) for which there is insufficient data.

TR-40 November 1971

PREDICTION OF GROUND-SHOCK-INDUCED AIRBLAST OVERPRESSURES FOR SUBSURFACE EXPLOSIONS FROM PEAK VERTICAL SPALL VELOCITY

Snell, C. M. and Oltmans, D. L.

A technique is presented for the prediction of ground-shock-induced airblast overpressures resulting from the subsurface detonation of nuclear and chemical explosives. The technique is based on a theory and physical model, developed by D. N. Montan of the Lawrence Livermore Laboratory, which correlates ground-shock-induced airblast overpressures with the vertical velocity of the rising mound above the detonation point. The derivation of the theory is reviewed in detail and the model's predictions are compared with airblast overpressure values measured during almost a score of large-yield chemical and nuclear detonations. Appendixes provide supplementary information on the correlation between vertical surface velocities and induced overpressures, extend the theory to five- and seven-charge row detonations, and apply the theory to contained and mounding detonations and to detonations in a noncompetent saturated medium overlain with water.

C. NCG/EERL Technical Memoranda Abstracts

(Listed sequentially by report number)

TM 65-1 March 1965

COMPUTER CODE INPUT DATA AND PRINTOUT INTERPRETATION FOR THE A. V. SHELTON FALLOUT MODEL (FLIP)

Day, W. and Morris, G. A.

This memorandum is intended to assist Corps of Engineer Districts participating in the Nuclear Cratering Group's (NCG) Engineering Feasibility Study Program by making a computer technique for calculating fallout available to them. The actual computer work will be done by NCG for Districts involved in the Feasibility Study Program. The fallout model used is the A. V. Shelton model developed at the Lawrence Livermore Laboratory, Livermore, California. Directions are given for estimating the needed input data for both single charge detonations and multiple charge detonations. Figures are given for estimating the fraction of radioactivity escaping and the dimensions of the nuclear clouds produced by the detonation(s). Example tables are given for tabulating input data. Specific instructions are given, along with sample computer printout sheets, for plotting the final fallout pattern from the computed data.

TM 65-2 April 1965

PRE-SCHOONER GROUND SURFACE MOTION STUDY

Larner, K. L.

The procedure for measuring significant features of the ground surface motion associated with the four HE shots of the Pre-SCHOONER test series in basalt is described. Velocities are computed from approximations to the derivative of the vertical displacement against time curves as determined by study of high-speed motion picture films. The significant features include the vertical velocities as functions of time for ground surface particles at various distances from surface ground zero and the peak vertical velocities at SGZ as a function of the depth of burst. The times associated with the onset of venting and the velocities of the escaping gas clouds are measured and the two dimensional displacement of particles at different distances from SGZ are studied. Elevation profiles of the transient ground surface shape are presented with superimposed postshot measurements.

A detailed analysis of the sources of errors in the technique of measurement is presented so that the quality of the data may be kept in mind. Only enough interpretation to aid the understanding of the results is given. The results appear to give a consistent representation of the dependence of surface motion in basalt upon depth of burst. Results include relatively high early peak vertical velocities (106 ft/sec for scaled depth of burst of 203 ft/kt$^{1/3.4}$) and relatively large uplift of the ground surface beyond the true crater radius (10-17 ft) prior to falling back to the final rest position.

The relative merits of measuring ground motion versus measuring target motion is considered because of some discrepancies between the two approaches.

TM 65-3 May 1965

SURFACE GEOLOGY OF THE PRE-SCHOONER II AREA

Paul, R. A.

The Nuclear Cratering Group (NCG) is planning to conduct the Pre-SCHOONER II experiment, a 100-ton HE cratering detonation in hard, dry, noncarbonate rock. This experiment will be the final corollary HE detonation for the 100-kt SCHOONER Event.

As part of the site selection investigation for the HE experiment, NCG personnel mapped the surface geology of an area surrounding the SCHOONER site which was designated the Pre-SCHOONER II area. It encompasses about 10-1/2 mi^2 and includes the five proposed sites for the HE experiment.

The Pre-SCHOONER II area is located on the Brueneau Plateau of southwestern Idaho, a surface of low relief, gently sloping northward to the Snake River. The oldest rocks exposed in this region are members of the Idavada Volcanics. These rocks have been buried by successive flows of Banbury Basalt, which have filled the old topography and produced the nearly level plateau surface. Faulting has brought the Idavada

Volcanics surfaceward at the Schooner site, where they are exposed as a NW-trending group of rounded hills.

Within the Pre-SCHOONER II area, the exposed members of the Idavada Volcanics include two or more felsite flows capped by a vitrophyre unit. The resistant felsite flows form the higher topography, with the less resistant vitrophyre occupying the lower slopes and valleys in the area. Banbury Basalt flows surround the Idavada Volcanics and locally invade them along old topographic lows. Covering nearly the entire surface of the area is a blanket of loess with incorporated detritus and residual soils.

Of the five proposed sites for the Pre-SCHOONER II experiment, four are located in the exposed sequence of Idavada Volcanics. At Sites #2, #3, and #4 felsite is overlain by vitrophyre. Site #1 is located entirely within a felsite sequence and Site #5 is located in Banbury Basalt. Based upon the information gained from the site selection investigation, NCG selected Site #2 for the experiment. It is located in a shallow flat-bottomed valley with approximately 27 ft of vitrophyre overlying felsite. This sequence is similar to that at the SCHOONER site.

TM 65-4 August 1965

POSTSHOT FIELD INVESTIGATIONS, BUCKBOARD MESA, NEVADA TEST SITE

Frandsen, A. D.

This memorandum presents the exploration techniques and results of the postshot excavation programs conducted by the U. S. Army Engineer Nuclear Cratering Group at the sites of the Pre-SCHOONER Charlie, Pre-SCHOONER Delta, DUGOUT and SULKY craters on Buckboard Mesa at the AEC Nevada Test Site. The scope of the postshot excavation program included determination of: (1) true crater radius dimensions; (2) extent of lip upthrust; and (3) bulk densities of the ejecta and fallback material.

The results of the postshot investigations are limited but appear to be reasonable and consistent. Bulk densities of the ejecta and fallback varied from 97 to 119 lb/ft^3. The measured values for true crater radius and lip upthrust showed some variance within individual craters, however, this is probably due to the strong influence of pre-existing joint systems. Because of the nature of the SULKY crater, no values were obtained for ejecta fallback bulk density, lip upthrust, or true crater radius.

TM 65-5 July 1965

ANALYSIS OF KNOX FALLOUT PREDICTION SYSTEM (KFOC)

Morris, G. A.

This memorandum presents an analysis by the author of the basic computations done in predicting fallout using the Knox Fallout prediction system (KFOC). Much of the information was obtained by examination of a FORTRAN computer printout of the

system. Available with the system but not discussed here is a plotting routine for final pattern display.

All information included in this memorandum other than the conclusions is based on notes or information obtained from persons working with the system. This paper is an attempt to present these data together in a concise manner.

The KFOC system is of interest because it is more versatile than, and will in the near future probably replace, the present prediction system (FLIP) used at Lawrence Livermore Laboratory.

It is concluded that although the KFOC system is not at this time operational it offers significant advantages over the (FLIP) system in versatility and application to large-scale nuclear excavation projects.

TM 65-6 (Secret-RD) June 1965

METHOD FOR PREDICTING DOSE RATE PATTERN AT VARIOUS TIMES FOR MULTI-DETONATION EXCAVATION PROGRAMS (U)

Day, W. C.

TM 65-7 July 1965

GROUND WATER CONTAMINATION STUDY AND EVALUATION

Cooper, R. A.

The literature pertaining to the redistribution of radionuclides by ground water is reviewed and a method for evaluating the ground water contamination hazard associated with nuclear excavation is presented. An equation representing the distribution of activity as a function of distance and time is developed in a manner similar to that presented by Higgins

Several factors influencing the redistribution of radionuclides by ground water reduce the probability of serious contamination problems. The most effective of these factors is the exchange of radionuclides between the solution and solid phases in the aquifer. This exchange limits the amount of activity available for transport at any given time and thereby retards the rate of radionuclide transport. In most cases, the radionuclide flow rate will be so slow that the concentrations of radionuclides will decay to tolerance before they are transported any appreciable distance. There will, however, be some situations in which conditions will allow a more rapid rate of radionuclide transport. Under these conditions, activity can be transported in hazardous concentration for a considerable distance. Preexplosion data on the hydrology of the project site will be necessary in order to evaluate the ground water contamination hazard.

TM 65-8 November 1965

STUDY OF THE SHAPE AND SLOPE OF EXPLOSION-PRODUCED CRATERS

Hughes, B. C., Benfer, R. H., and Foster, F. H.

The purpose of this memorandum is twofold: (1) to determine which geometric shape, a parabola or a hyperbola, better approximates the average apparent crater cross section for explosion-produced craters in alluvium and basalt; and (2) to develop an equation which can be used to predict the crater crater cross section

Twenty craters, seven in basalt and thirteen in alluvium, were studied. The depths of burst ranged from 1.9 to 635 ft, a scaled depth range of 2.33 to 185.5 $ft/kt^{1/3.4}$. Yields ranged from 950 lb to 100 kt. The craters investigated were produced by the following energy sources: nitromethane—9, TNT—8, and nuclear—3.

For each detonation, the study consisted of: (1) determination and plotting of the average apparent crater cross section; (2) plotting of the parabola and two of the hyperbolas that pass through the maximum depth (D_a) and the radius (R_a) of the average apparent crater cross-section; and (3) visual comparison of the shapes to determine which shape best approximated the average apparent crater cross section. Of the 20 craters studied, 18 were better approximated by hyperbolas. An equation was developed for predicting the average apparent crater cross section.

TM 65-9 October 1965

PROJECT ZULU: A ONE-POUND HIGH EXPLOSIVE CRATERING EXPERIMENT IN SCALPED AND REMOLDED DESERT ALLUVIUM

Hughes, B. C. and Benfer, R. H.

During the period July to September 1964, the U. S. Army Engineer Nuclear Cratering Group conducted Project ZULU at the Nevada Test Site. The experiment consisted of the detonation of twenty-six 1-lb C-4 charges in scalped and remolded desert alluvium at the Nevada Test Site. The purpose of the experiment was to determine the suitability of scalped and remolded desert alluvium as a cratering medium for future laboratory-scale tests to be conducted at Site 300, Lawrence Livermore Laboratory, Livermore, California. The cratering medium used for Project ZULU was placed under very carefully controlled conditions of moisture, density, and gradation to insure uniformity. Continuous density and moisture measurements of the medium were taken to define the engineering properties of the in-place material and to provide a basis for interpretation of cratering results.

The objective of Phase I of the experiment was to determine the reproducibility of crater dimensions (apparent crater depth and radius) in the selected cratering medium. The detonation of charges at a depth of burst of 2 ft produced craters with an average radius of 2.50 ft (fractional standard deviation, S, of 3.9%) and an average depth of 1.38 ft (fractional standard deviation, S, of 7.2%).

The objective of Phase II of the experiment was to develop cratering curves for the scalped and remolded desert alluvium. The cratering curves resulting from this phase of the experiment showed a rapid decrease in apparent crater dimensions for depths of burst greater than optimum. A similar phenomenon has been observed from cratering detonations (20 ton-100 ton level) in hard rock.

The results of Project ZULU indicated that small changes in the moisture and density of the scalped desert alluvium produce significant variations in apparent crater dimensions. In order to obtain reproducible crater dimensions, the properties of the alluvium had to be rigidly controlled. Based on these findings it was concluded that a material such as moist well-graded sand should be used for the Site 300 laboratory-scale cratering experiments rather than scalped desert alluvium. It is felt that a moist sand medium will yield reproducible cratering results without necessitating the extremely rigid control of its engineering properties that the scalped desert alluvium required.

TM 65-10 July 1965

ANALYSIS OF THE A. V. SHELTON FALLOUT PREDICTION SYSTEM (FLIP CODE)

Lattery, J. E.

Sensitivity of the Shelton Fallout Prediction System to changes in input parameters was determined by developing a number of patterns under somewhat idealized conditions. Principal parameters investigated were cloud dimensions, weather data and input activity.

Patterns which were developed based on very little wind shear were more readily influenced by parameter changes than those developed with a significant amount of wind shear.

Pattern integration was performed to compare activity residing in the field with input activity.

It was found that although general trends can be established it is not possible to arrive at a direct measure of sensitivity of patterns to input data.

TM 65-11 November 1965

GEOLOGIC EXAMINATION OF THE ACCESS SHAFT AND EXPLOSIVE CAVITY FOR PROJECT PRE-SCHOONER II

Paul, R. A.

As a part of the Corps of Engineers' on-going High Explosive Experimental Cratering Program, the U. S. Army Engineer Nuclear Cratering Group executed Project Pre-SCHOONER II on 30 September 1965. This experiment was designed as a correlation shot on the proposed 100-kt SCHOONER nuclear cratering experiment planned for execution by the Atomic Energy Commission.

In conjunction with the Pre-SCHOONER II preshot geologic investigations, the access shaft and explosive cavity for the experiment were examined by geologists of the NCG. The purpose of the examination was threefold: to describe the rock materials which would be involved in the cratering experiment; to determine the type, frequency, openness and extent of structural planes within the rock; and to obtain a photographic record of the shaft and cavity.

From the top of rock to approximately 28 ft in depth, the access shaft passes through vitrophyre breccia. This material is composed of an altered volcanic glass matrix containing angular fragments of relatively fresh black volcanic glass. The material is a tightly welded mass, nearly free of structural planes.

From approximately 26 to 28 ft in depth, the access shaft passes through a transition zone between vitrophyre breccia and glassy felsite. The glassy felsite gradually changes to a felsite with a cryptocrystalline groundmass over the interval from 28 to 40 ft in depth. The felsite is generally hard and competent, except for a friable zone from 42 to 50 ft in depth.

The access shaft opens into the explosive cavity at approximately 61 ft in depth. The felsite exposed in the cavity is competent, except for a few small friable patches. The felsite is intersected by three primary joint sets, dividing the rock into slabs with average dimensions of 4 in × 8 in × 1 ft.

The stratigraphic sequence and rock materials exposed in the access shaft and explosive cavity are essentially the same as that inferred from previous investigations. This examination of the access shaft and explosive cavity did not reveal any conditions inherent in the rock materials which might compromise the experiment.

TM 65-12 November 1965

PRELIMINARY MODEL FOR ANALYSIS OF NUCLEAR CRATER SLOPE STABILITY IN A HOMOGENEOUS MEDIUM

Peck, J. W.

This memorandum describes a simple model that may be applied to the stability analysis of crater slopes formed in a homogeneous medium. The model is developed by combining the recognized method of slip circle analysis which assumes that a slide occurs along a circular surface with the geometry of nuclear explosive produced craters. The procedures developed for this analysis are in a general form; consequently, they may be applied to stability investigations involving any size explosive yield and any material for which the cohesion, friction angle and density may be estimated.

In applying a simple model it is desirable to have information available that clearly identifies the effect of varying the important parameters. The results of this analysis clearly indicate the significance of the size of the explosive yield and the medium properties of density, cohesion and angle of internal friction.

The scope of this presentation does not include consideration of slope stability in a rock medium characterized by adverse geology.

TM 65-13 November 1965

A PRELIMINARY ASSESSMENT OF OVEREXCAVATION AS A POSSIBLE SOLUTION TO POTENTIAL SLOPE STABILITY PROBLEMS

Peck, J. W.

Overexcavation has often been suggested as a possible means of maintaining channel dimensions in those reaches of a nuclear excavated canal of potentially unstable slopes. The overexcavation concept involves the use of a higher yield than the minimum size required to produce desired navigation prism dimensions in order to provide a sufficiently large crater that the ultimate long-term stable configuration will meet the minimum channel criteria.

The purpose of this paper is to make a preliminary quantitative assessment of the feasibility and limitations of overexcavation as a solution to stability problems by examining the mathematical relationship derived from the assumed conditions and the practical implications of employing such a technique. This will be accomplished by deriving the general relationships that result from assumptions concerning crater geometry and stability and applying these relationships to a study of sea-level canal Route 17A in the Darien Region of Panama.

TM 65-15 November 1965

PRELIMINARY REPORT OF THE ANALYTIC STUDY OF TIDE-INDUCED CURRENTS IN A SEA-LEVEL CANAL

DeFord, D. D.

This study was done with a dual purpose: (1) to develop a rapid and reliable system for computing the current velocities in a sea-level canal resulting from differential entrance tides; and, (2) to predict the tidal current velocities in specific Atlantic to Pacific sea-level canal configurations.

The procedure used was to computerize the Pillsbury method for the calculation of current velocities in a sea-level canal. A brief summary of Pillsbury's development of the method is presented as well as a step by step outline of the mechanics of the solution to a current velocity problem. The complete computer program is presented in Appendix A.

The results of the initial case studies show that under the worst probable conditions velocities will not exceed 7.5 knots in any of the Panamanian alignments or 2.8 knots in the Colombian alignments. The studies further show that under mean conditions the Panama routes have a maximum velocity of 4.8 knots and in Colombia 2.1 knots. This study does not include varying the channel dimensions at constrictions to reduce the maximum velocity. The study further shows that, for Route 17A, the duration of current velocities in excess of 5 knots is 5 hr 52 min per 12 hr tidal cycle for the maximum 2% frequency. These tides occur only once a month. For the 50% frequency tide, mean conditions, the current does not reach 5 knots.

As a result of parametric studies in which the friction coefficient and the surface head were varied several conclusions are drawn.

As the friction coefficient is lowered the maximum velocity approaches some assymptotic value which appears to be not much greater than the maximums calculated in this study.

Channels are more sensitive to change in the friction coefficient in the higher range of coefficients than in the lower range.

Longer channels are less sensitive to head and friction changes than shorter channels.

In very long channels the entire head does not become effective in producing flow because of the reaction time of the channel to the surface head.

Longer channels result in reduced velocities because of increased total frictional resistance.

When substantial lengths of dredged channel, with its substantially reduced cross-section, are considered in combination with channels produced by nuclear excavation the friction coefficient of the dredged section predominates with little effect from varying the coefficient in the cratered channel.

Pending the establishment of some criteria for maximum permissible velocity or maximum acceptable duration of velocities in excess of some limit no conclusions can be drawn as to the suitability of one alignment as compared to another.

The computational system is felt to be sufficiently accurate to be used in the preliminary feasibility studies. It is also felt that with some refinement of the computer program and a reliable evaluation of the friction coefficient the program will be suitable for use in the design phase of a sea-level canal.

TM 66-1 (Secret RD) January 1966

INVESTIGATIONS OF THE RESULTING CRATER SLOPE AND LOCAL FALLOUT RADIOACTIVITY TO BE EXPECTED WHEN A NUCLEAR DEVICE IS BURIED AT A SCALED DEPTH LESS THAN OPTIMUM AND THE YIELD VARIED TO GIVE THE REQUIRED CRATER DEPTH (U)

Day, W. C.

TM 66-2 January 1966

THE KNOX FALLOUT PREDICTION SYSTEM'S (KFOC) RESPONSE TO CHANGES IN INPUT PARAMETERS WHICH DEFINE THE ACTIVITY-PARTICLE SIZE DISTRIBUTION

Morris, G. A.

The Knox Fallout Prediction System was run with different sets of the parameters (mean μ and deviation σ) of the lognormal distribution of activity-particle size used in the Fallout Prediction System to determine the system response compared to the expected response. Runs were done using different lower limits of particle size, R_s, to find what effect this had on the output.

It was found that the system responds to changes in parameters as would be expected and that an R_s of 20 microns seems to be the optimum for use with $\mu = 3.8$ and $\sigma = 0.69$ for the conditions of this investigation.

TM 66-3 February 1966

SUMMARY OF THE OPINIONS OF THE TECHNICAL ASSOCIATES TO THE ATLANTIC-PACIFIC INTEROCEANIC CANAL STUDY COMMISSION AND OPINIONS OF THE CONSULTANTS TO THE WATERWAYS EXPERIMENT STATION WHICH ARE RELATED TO THE NUCLEAR EXCAVATION CUTS

Slazak, W. J., Peck, J. W., Fisher, P. R., Holmes, R. S.

A major research task is to develop the means of predicting the stability of nuclear excavated cuts. The nature of the environment and the natural forces acting must be taken into account in any preliminary stability analysis. The medium surrounding an explosively produced cut is altered by the explosion. These changes in the medium must be considered in the stability analyses. The "state of the art" is analyzing the stability of explosively produced cuts is being applied to a sea-level canal channel (as to an aid in formalizing the procedure of analysis and to ferret out areas).

Opinions of the consultants, foremost in their field, have been received on the problem. The state of the art as presented to these consultants is included in this memorandum. The opinions of the consultants have been summarized under applicable subject headings with a separate sheet for each problem area. It is envisioned to use this memorandum as a working document adding new problem areas and approaches to problem areas already isolated.

TM 66-4 February 1966

EARLY ESTIMATES OF RADIOACTIVITY IN THE FALLOUT FIELD

Cooper, R. A.

A method for determining early estimates of fallout data is developed and an example which illustrates the method is presented. The method is intended to give estimates of the number of kilotons of fission products in the fallout field, the fraction out, and a sketch of the fallout pattern within a few hours after a nuclear cratering detonation.

The method was applied to primary data from some past cratering events and found to be accurate to within a factor of 2.

TM 66-5 February 1966

PHENOMENOLOGY OF THE FORMATION OF A CRATER BY DETONATION OF A ONE-POUND CHARGE BURIED AT A DEPTH OF BURST OF TWO FEET IN THE ZULU II MOIST SAND

Bening, R. G. and Larner, K. L.

Evidence from several experiments associated with the ZULU II crater detonations suggest a phenomenological description of important phases of material displacement during crater formation in the ZULU II series. This paper consists of a description of 12 drawings which represent the history of deformation and displacement of the ground subsurface for a 1-lb spherical charge of C4 buried at a depth of 2 ft. Estimates of time elapsed have been included and are based upon the time dependent shape of the ground surface observed in high-speed motion picture photography.

The diagnostic experiments in the ZULU II tests include the following:

a. preshot and postshot positions of colored sand lenses;

b. displacements of ball bearings placed at known positions in the ground prior to detonation;

c. depth of penetration readings for a long thin rod pushed vertically into the postshot medium at known locations;

d. ground surface motion obtained from high-speed motion picture photography.

Many qualitative features of the subsurface deformation were inferred from study of the high-speed movies of small-scale cratering experiments performed by Prof. A. S. Vesic under Contract No. DA-22-075-Civeng-63-22. In those experiments, dense, dry sand was prepared in a $30 \times 30 \times 17$ in. box with a transparent Plexiglas wall, against which a hemispherical charge of 0.837 g of lead azide was exploded at different depths.

TM 66-6 Revised August 1966

THE EFFECTS OF INHOMOGENEITIES IN A CONTROLLED SAND MEDIUM ON SMALL SCALE HIGH EXPLOSIVE EXPERIMENTS

Christopher, W. G.

This memorandum presents the experimental techniques, methods of analysis, and results of four of the detonations of Project ZULU II. This project is being conducted by the U. S. Army Engineer Nuclear Cratering Group at the University of California Lawrence Livermore Laboratory's High Explosive Test Facility, Site 300, near Livermore, California. The tests to date have consisted of a series of single and row 1-lb C4 charges detonated in a moist concrete sand.

The four detonations analyzed in this memorandum were buried at a nominal depth of 2 ft. One of the charges were in a homogeneous sand medium. The other three had certain inhomogeneities introduced in the immediate vicinity of the shot point.

The objective of this investigation is to analyze the effects of known density variations in controlled small-scale experiments.

The order of importance of the four phenomena compared is as follows: (1) the shape of the mound during its growth from zero time to the time of venting of the cavity gas at about 200 msec; (2) the directions of displacement of the surface motion targets during this same period; (3) the postshot profiles of the surface and the subsurface profiles of disturbed material; and (4) the velocities of the surface motion targets.

The results indicated that a relatively rigid object (a basketball) had the effect of reflecting energy away from itself and impeding the movement of material over and beyond the object. The lower-density objects (voids) caused the gas cavity to migrate and expand into the void, thus losing pressure, expanding to a larger size at a deeper level, and, therefore, having less energy remaining to eject the material from the ground and form a crater.

TM 66-7 November 1966

CONSOLIDATED REPORT: OPERATION BREAKUP, FY 66
ICE CRATERING EXPERIMENTS, BLAIR LAKE, ALASKA

Kurtz, M. K. Jr.

Operation BREAKUP, FY 66, was a series of small, single and row charge, chemical explosive detonations fired in fresh water to crater the overlying sheet ice. The experiments were conducted by the U. S. Army Engineer Nuclear Cratering Group in the winter of 1966 under 3 ft of ice at Blair Lake, 33 mi SSE of Fairbanks, Alaska. In order to obtain information concerning the civil application of ice cratering, the operation had the following purposes: (1) to determine the cratering effects of single and row charges detonated below an ice layer; (2) to study bubble coalescence; and (3) to support theoretical studies of cratering physics. Technical programs included crater measurements, ice surface motion, engineering properties, and fish surveys.

It is concluded that: (1) the relationship between depth of detonation and ice crater radius has been defined for 136-lb C4 spherical charges for various experimental conditions; (2) shock wave reflection from the lake bottom did not appear to enhance the crater dimensions; (3) row charge crater dimensions were defined for three charge spacings; (4) cracks appeared to propagate better from larger yield explosions under ice of the same thickness; (5) there did not appear to be any evidence of bubble coalescence in the experiments; (6) commonly used scaling laws may be used to estimate the effects of higher yield ice cratering explosions; (7) the procedures used are adaptable to civil application; (8) a detailed evaluation was made of the effects of under-ice explosions on fish; and (9) maintenance of open water gaps created by explosions is affected by re-freezing and water currents.

Practical engineering applications of the BREAKUP results are illustrated by use of examples.

TM 66-8 September 1966

CLOUD DIMENSIONS FOR CRATERING EXPLOSIONS

Day, W.C.

An empirical approach to the prediction of cloud dimensions for chemical high explosive cratering detonations and nuclear cratering detonations is presented.

Data from previous chemical and nuclear events are summarized and curves are presented which permit easy scaling to other proposed events. The effects of atmospheric conditions and the cratered medium on cloud development are discussed. A method for predicting expected cloud dimensions from multiple charge events is presented and evaluated in light of the limited experience in this area. An attempt has been made to suggest reasons for variances observed in the data points which should be of some help in analyzing data from future events.

TM 66-9 (Secret RD) October 1966

STUDY ON TACTICAL FALLOUT PREDICTION METHOD FOR THE MILITARY ENGINEERING APPLICATION OF NUCLEAR EXPLOSIVES (U)

Morris, G.A. and Lattery, J.E.

TM 66-11 July 1966

A COMPUTER SOLUTION USING THE PILLSBURY METHOD FOR COMPUTATION OF TIDES AND CURRENTS IN NUCLEAR EXCAVATED, CONVENTIONALLY EXCAVATED OR COMBINATION CHANNELS

Bening, R.G.

This report summarizes work completed to date by the Nuclear Cratering Group (NCG) in the field of Tidal Hydraulics. The efforts of NCG in this field have been undertaken with a dual objective: (1) to develop a rapid and reliable system for computing the currents in a nuclear excavated, conventionally excavated or combination channel with a tidal variation on one or both ends; and (2) to predict the tidal currents in an interoceanic sea-level canal across the Central American Isthmus whether excavated by nuclear or combined nuclear and conventional techniques. To accomplish these objectives, the method of computation proposed by Brig. General G.B. Pillsbury in his treatise "Tidal Hydraulics" has been used. The complexity and length of this method of solution makes the use of the computer desirable. The program presented is written in FORTRAN II language for use on the IBM 7094 computer.

A brief summary of the Pillsbury method is presented. The computer program is described in detail and a discussion of the assumptions and limitations is presented. Appendix A includes appropriate extracts from Pillsbury's "Tidal Hydraulics." Appendix B includes complete instructions for use of the computer program and a complete

Fortran listing. Appendix C contains the solution of two example problems, one for a conventionally excavated channel and one for a nuclear excavated channel.

Those portions of the memorandum pertaining to a nuclear excavated channel have been written assuming the reader has a basic understanding of nuclear excavation technology.

TM 66-12 August 1966
Revised August 1966

STEM DESIGN FOR TACTICAL EMPLACEMENT OF NUCLEAR EXPLOSIVES

Kurtz, M. K. Jr.

The purpose of this memorandum is to present recommended stem design for tactical emplacement of ADM's based on current philosophy of stem design for nuclear explosives. A review of the evolution of present concepts and full stemming criteria was made. A discussion of tactical considerations is given, with attention to the effects of partial or no stemming, emplacement configurations, and practical problems which affect design. It is concluded that: (1) full stemming criteria for civil applications of nuclear explosives, while not appropriate for tactical emplacement of ADM's, should be used for military construction operations; (2) the best overall stem design for tactical stemming is one in which dry sand or earth is used to completely fill the hole; (3) the effect of an emplacement hole partially filled with stem material cannot be evaluated; and (4) sandbag or liquid stemming is better than no stemming or partial stemming with openings; sandbags are preferred over liquids. It is recommended that the stem design for tactical emplacement of ADM's developed in the study be used as current guidance.

TM 66-13 September 1966
Revised April 1967

A MODEL OF THE FORMATION OF THE NEPTUNE CRATER

Christopher, W. G.

The NEPTUNE Event, fired on 14 October 1958 at the Nevada Test Site, was a nuclear detonation with a yield of 115 ± 15 tons. The device was emplaced at the end of an 185-ft "buttonhook" drift beneath a 30-deg slope on the side of Ranier Mesa. The nearest free surface was 85.4 ft, a scaled depth of burst 162 ft/kt$^{1/3.4}$.

The apparent crater produced in the 30-deg sloping mesa was approximately 100 ft in radius and 35 ft in depth, and had a volume of approximately 20,000 yd^3. Approximately 34,000 yd^3 of material slid down the slope for at least 800 ft.

Several reports written about the event describe the preshot conditions obtained from topography and geologic exploration, the postshot conditions obtained from geologic exploration, and the phenomena of the formation of the NEPTUNE crater. However, a discrepancy appears in the explanations of the phenomena of the crater formation in that the maximum velocity of the rising mound is taken as 35 ft/sec. If this

were, in fact, the maximum velocity of the peak of the rising mound, it would be difficult to explain the resulting crater.

On the basis of a reexamination of the high-speed film of the movement of the earth surface, it was concluded that the rising mound had a much higher velocity than previously reported. This increased velocity is more consistent with the large volume of material ejected from the crater. The locations of the points of massive venting give insight into the interaction of the sloping rock layers with the expanding gas cavity.

Small-scale half space models of charges under 30-deg slopes have been photographed with high-speed cameras and have provided additional insight into this particular phenomena.

The hypothesis presented in this report is a synthesis of all of the above information. In following the sequence of the cratering mechanism presented herein, the final configuration appears logical.

TM 66-14

July 1966
Revised May 1967

ANALYSIS OF SURFACE MOTION PHENOMENA OF ONE-POUND ZULU II CHARGES OF VARYING DEPTH OF BURSTS

Christopher, W. G.

This memorandum presents the experimental techniques, methods of analysis, and results of an investigation of the surface motion phenomena of a number of detonations of Project ZULU II. This project is being conducted by the U. S. Army Engineer Nuclear Cratering Group at the University of California Lawrence Livermore Laboratory's High Explosive Test Facility, Site 300, near Livermore, California. The detonations analyzed in this memorandum varied in depth of burst from 1.40 to 2.24 ft in moist concrete sand compacted under closely controlled conditions.

The investigation compares the surface motion phenomena of detonations in the optimum range of depths of burst for the production of craters with the surface motion phenomena of detonations which are too deep to produce useful craters.

To accomplish this analysis the following aspects of surface motion were considered: (1) the velocity histories of selected points along the surface; (2) the relationship between magnitude of velocity and distance from SGZ; (3) the relationship between depth of burst and peak surface velocities; and (4) the relationship between the initial and final positions of surface particles.

The results indicated that: (1) the maximum surface velocity of ZULU II detonations can be accurately predicted over a wide range of depths of burst; (2) whether or not a useful crater will be formed depends upon the magnitude of velocity achieved as well as the height and shape of the mound when the forces of the detonation cease to accelerate the particles; (3) the subsurface material, especially in noncratering shots, does not initially move radially outward from the shot point, but rather in a direction almost normal to the surface; and (4) the direction of surface particle movement is less indicative of the direction subsurface particle movement for detonations at deeper depths of burst than for shallower depths of burst.

TM 66-15 April 1967

ANALYSIS OF THE PHENOMENA WITHIN THE IMMEDIATE CRATER AREA RESULTING FROM THE DETONATION OF ONE-POUND ZULU II CHARGES

Christopher, W. G.

The purpose of this memorandum is to present data obtained in the investigation of the cratering mechanism exhibited in the detonation of one-pound charges at varying depths of burst in Project ZULU II basalt modeling medium. Project ZULU II is being conducted by the U. S. Army Engineer Nuclear Cratering Group at the University of California Lawrence Livermore Laboratory's High Explosive Test Facility, Site 300, near Livermore, California. The tests to date have consisted of a series of single and row 1-lb C4 charges detonated in a carefully placed moist concrete sand medium.

The five detonations investigated in this memorandum varied in depth of burst from 1.40 to 2.50 ft. The objective of the investigation was to compare the cratering mechanisms exhibited by: (1) detonations which produce the largest craters (-1.4 and 1.6-ft depths of burst); (2) deeper detonations which produce craters (-1.8 and 2.0 ft depths of burst); and (3) detonations too deep to produce a crater (-2.5 ft depth of burst).

The cratering mechanisms of these detonations were analyzed through the use of the following data collected for each detonation:

1. The surface motion of the ground above each detonation;
2. The movement of specific subsurface particles throughout the area above the detonation, through the use of coded ball bearings;
3. The postshot configuration of the ground surface;
4. The limit of the zone of significant disturbance of the medium around each detonation; and
5. The final versus initial position of the subsurface material through the use of six-in. layers of colored sand placed over each detonation.

It is concluded that the cratering mechanisms vary significantly with depth of burst. For the detonations which produce the largest craters the peak surface velocities are very high (90 to 160 ft/sec), the subsurface particles are ejected out of the crater at velocities close to the surface particles above them, and the subsurface material which is ejected is scoured, or sheared, out by the force of the detonation, exposing the shot point. There is little fallback within the crater.

For the deeper detonations, which produce craters, different phenomena are observed. The peak surface velocities are much lower (50 to 80 ft/sec) than before; the subsurface particle velocities are significantly lower than surface particle velocities; and the ejection of the material from the crater is a slower process which is accompanied by a slumping, or sloughing, of material into the true crater while the majority of the ejected material is in the air. Fallback then is deposited on top of the sloughed material causing a much shallower crater than for the shallower shots. The shot point is well covered.

For the detonation so deeply buried that no apparent crater is produced, the surface and subsurface velocities are the lowest of all; the sloughing phenomena is observed as in the previous case; and an "overturning" of subsurface material is observed near the edge of the true crater. Also, the material near the vertical axis through shot point is highly mixed and jumbled and material is mounded above the preshot surface.

TM 66-16 October 1966

TIDAL HYDRAULICS

Bening, R. G.

This paper includes a brief discussion of the results of theoretical investigations and model tests conducted during the 1947 Isthmian Canal Studies, a description of two of the nuclear excavated channels currently being studied, a summary of predicted currents based upon currently available data and the results of parametric studies which illustrate the effect of certain parameters on the computed currents. The method of computation of tidal currents proposed by Brig. General G.B. Pillsbury in his treatise, "Tidal Hydraulics," has been used as a basis for these studies.

The computational procedure has been computerized, and is described in detail in NCG TM 66/11. All computations reported herein have been accomplished using this technique except for those results extracted from previous studies.

TM 66-17 October 1966

TIDAL HYDRAULICS—HYDRAULIC CHARACTERISTICS OF TIDAL CHANNELS PRODUCED BY NUCLEAR EXCAVATION TECHNIQUES

Slazak, W. J.

The hydraulic characteristics of tidal channels of nuclear-excavated cuts are investigated by use of the General Pillsbury method of solution of the tidal equations. Equivalence is established between the propagation equations and the steady state condition. The method of General Pillsbury is described as a perturbation of the steady state solution. The Pullsbury method is concluded to be suitable for the comparison of alternative channels.

TM 66-18 October 1966

VARIATION OF PROJECT ZULU II CRATER DIMENSIONS VERSUS MEDIUM PROPERTIES

Benfer, R. H.

This memorandum reports on the observed variation of apparent crater dimensions (radius and depth) of 1-lb C4 detonations conducted at the same depth of burst. The variation in dimensions is greatest for a depth of burst of 2 ft. The dimensions of

the 2-ft shots are compared with medium density, moisture content, CBR, and maximum SGZ vertical velocity in order to establish a relation to explain the variation in dimensions. No such relation was found.

TM 66-19 November 1966

ZONE OF BULKING, PROJECT SULKY

Fisher, P.R.

The purpose of this memorandum is to discuss methods of determining the extent and character of the zone of bulking occurring at cratering events in rock media. Project SULKY was chosen as an example to perform computations upon because nearly all the produced rubble could be accounted for. The effective porosity computations indicated that the effective porosities surrounding the produced rubble chimney were changed from a preshot effective porosity of 2% to an induced porosity of 25% immediately adjacent to and in rubble mound and rubble chimney. Volume computations indicate that, of the total volume of disturbed materials, only 2% could not be accounted for by the computed effective porosities.

TM 66-20 December 1966

A REPORT OF THE SCOPE AND PRELIMINARY RESULTS OF PROJECT PRE-GONDOLA I

Kurtz, M.K. Jr.

Project Pre-GONDOLA I was a series of chemical explosive single-charge cratering experiments in weak, wet clay-shale conducted by the U.S. Army Engineer Nuclear Cratering Group (NCG) as a part of the joint Atomic Energy Commission-Corps of Engineers nuclear excavation research program. The purpose of the Pre-GONDOLA I Cratering Calibration Series was to calibrate the project site with respect to its cratering characteristics and to provide a basis for design of the proposed 100-ton level Pre-GONDOLA II and III row-charge cratering detonations in the same medium.

The Pre-GONDOLA I detonations occurred in Valley County, near the edge of the Fort Peck Reservoir approximately 18 mi south of Glasgow, Montana.

TM 67-1 February 1967

PREDICTED DOSE RATES WITHIN THE NUCLEAR CRATER AND LIP AREA

Day, W.C.

This report deals with the prediction of gamma dose rates in the nuclear crater and the crater lip area formed by an underground nuclear explosion at near optimum depth of burst. A simple method is developed for making these predictions considering both fission products and induced gamma emitting radionuclides. When applied to two

past nuclear cratering events, the method gives results within 5% of those actually observed. The method will give a base from which to predict for the larger yield cratering experiments, and perhaps add some incentive to making timely measurements that may be used to check it.

TM 67-1a (Secret RD) February 1967

PREDICTED DOSE RATES WITHIN THE NUCLEAR CRATER AND LIP AREA (U)

Day, W. C.

TM 67-2 January 1967

CHANNEL CRITERIA FOR THE EVALUATION OF THE TIDES AND CURRENTS IN A NUCLEAR EXCAVATED SEA-LEVEL CANAL

Bening, R. G.

The purpose of this memorandum is to present channel criteria for use in the evaluation of the tidal currents in a nuclear excavated sea-level canal. These criteria are based upon nuclear excavation technology currently being used in the Interoceanic Canal Studies.

The following specific information is presented in this memorandum:

1. A brief summary of the procedure used to describe the nuclear excavated channel cross section.

2. A description of Route 17A in Panama based upon actual device yield, device location, and channel depth at each device location.

3. A description of Route 17A at 500-ft intervals using a hypothetical device yield and interpolated channel depth.

4. The results of computations based upon the description in paragraph 3 above, accomplished using the Pillsbury Method of Solution.

TM 67-3 March 1967

ENGINEERING PROPERTIES OF CRATERS

Fisher, P. R.

The purpose of this memorandum is: (1) to describe the type of field investigations used to define the pre- and postshot properties of explosively-produced craters, (2) to summarize the results of crater properties investigations to date, and (3) to present methods used in predicting postshot crater properties based on preshot investigations.

The memorandum is organized into four chapters. Chapter 1 defines the purpose of the memorandum, offers a definition of crater properties, and describes the current crater properties research program. Chapter 2 offers guidance on field and laboratory

investigation methods applicable to preshot crater properties investigations. Chapter 3 summarizes results of postshot field investigations at selected cratering experiments, compares the results of pre- and postshot investigations, and describes methods used in predicting postshot properties. Chapter 4 summarizes the content of the memorandum and offers broad criteria for the prediction of postshot crater properties.

TM 67-5 March 1967

AN "L" SHAPED ROW CHARGE CRATERING EXPERIMENT

Christopher, W. G.

The purpose of this memorandum is to present the results of a row charge cratering experiment in which the charges were in a "L" array. Each charge was 1 lb of C4 buried at a depth of burst of 2.00 ft with a spacing between charges of 2.30 ft, or one single-charge crater radius. The charges were emplaced in ZULU II basalt-modeling medium. Project ZULU II is being conducted by the U. S. Army Corps of Engineers Nuclear Cratering Group at high explosive test facilities near Livermore, California, under the joint AEC/CE nuclear excavation research program.

The results of this experiment indicated that the detonation of a row of charges in a "L" array produces a smooth, continuous "L" shaped crater of approximately the same size as would be produced by a linear row array of charges of similar size, depth of burst, and spacing.

The experiment demonstrates the feasibility of constructing, with one detonation, a row crater incorporating a centerline change of direction up to 90-deg. This offers an attractive alternative to a more complicated excavation design in which two row charge craters are connected at an angle with successive detonations.

TM 67-6 April 1967

THE EUCLID CODE, A COMPUTER PROGRAM FOR THE CALCULATION OF THE NUCLEAR EXPLOSIVE REQUIREMENTS FOR A NUCLEAR EXCAVATED CHANNEL

Bechtell, W. R.

The memorandum presents an updated description of the EUCLID code. The input data necessary for the use of the code is fully described. Also included are a flow chart and definition of variables.

TM 67-7 January 1967

TRACE ELEMENTS IN COMMON ROCK TYPES AND THEIR RELATIVE IMPORTANCE IN NEUTRON-INDUCED RADIOACTIVITY CALCULATIONS

Day, W.C. and Paul, R.A.

The chemical composition of the rock surrounding an underground nuclear detonation must be known or assumed when calculations of the resulting neutron-induced radioactivity are attempted. A typical chemical analysis of rock samples does not include certain trace elements which have high neutron-capture cross sections. A literature search was undertaken to determine the average and range of content of these trace elements in common rock types to permit an evaluation of their relative importance in neutron-induced radioactivity calculations.

The elements considered in the study were Dy, Gd, Eu, Sm, Nd, Cd, Ag, Co, Cr, V, Sc, Cl, S, B, and Li. Data are reported giving content of these elements in ten igneous rock types and three sedimentary rock types. The five elements Gd, Eu, Sm, B, and Cl were found to occur in most rock types in quantities which would significantly affect neutron-induced radioactivity calculations.

Calculations of induced radioactivity were performed for granite using maximum, average, and minimum trace element values obtained from the literature search. Calculations were also performed using average trace element values for four other igneous rocks and three sedimentary rocks. It is concluded that, in general, use of the average values for trace elements presented in this report is adequate for assessing the production quantities of radionuclides induced external to the device for use in feasibility studies for large scale excavation projects and other underground nuclear detonations when detailed chemical analyses of emplacement media are not available.

TM 67-8 July 1967

PRE-SCHOONER TARGET HORIZONTAL DISPLACEMENT AND VELOCITY HISTORIES

Christopher, W.G.

The purpose of this memorandum is to present the horizontal displacement and velocity versus time plots for the targets of the four Pre-SCHOONER detonations. In the surface motion report for Pre-SCHOONER these plots were not included because of their bulk. However, the plots are valuable as a means of better understanding the surface motion resulting from these detonations and the plots should be preserved.

Any reader examining these plots should first consult the surface motion report for a full explanation of the meaning of these plots and the notation on the plots.

TM 67-9 August 1967

A REPORT OF THE SCOPE AND PRELIMINARY RESULTS OF PROJECT PRE-GONDOLA II—ROW CHARGE CRATERING EXPERIMENT

Kurtz, M. K. Jr. and Day, W. C.

This report presents the scope and preliminary results of Pre-GONDOLA II. It is based on the 30-day reports of the various technical program officers. This compilation provides background information and interim data for use until final reports are issued. The Technical Director's Summary Report and the other technical program reports will include details of predictions, experimental procedures, analysis of data, and a final statement of conclusions.

TM 67-10 July 1967
Revised January 1968

PRE-GONDOLA SEISMIC DECOUPLING SERIES

Harlan, R. W., Christopher, W. G., and Redpath, B. B.

Two 1000-lb high explosive cratering detonations were conducted by the U. S. Army Engineer Nuclear Cratering Group (NCG) on 14 June 1967. The purpose of the experiment was to provide data on the cratering and seismic effects of a detonation decoupled from the medium. The following crater dimensions resulted:

Event	DOB*	R_a*	D_a*	R_{me}*
SD-1 (coupled)	17.3	25.1	10.5	361
DS-2 (decoupled)	17.7	23.7	10.5	348

*All dimensions in feet.

Contrary to expectations, the ground motion generated by the decoupled charge exceeded that from the coupled charge at all seven seismic stations. Maximum surface motion velocities of 140 and 160 ft/sec were observed for shots SD-1 and SD-2, respectively. The magnitude of these velocities is comparable to expected velocities based on experience gained during the Seismic Calibration Series.

An analysis of the Seismic Decoupling Series data indicated that neither larger craters nor lesser ground motions result from decoupling a cratering charge from the medium.

TM 67-14 September 1967

EXPLOSIVELY PRODUCING AN EMBANKMENT ACROSS A NARROW, STEEP-WALLED CANYON

Kleist, E. H.

This memorandum presents results of 1-lb laboratory scale high explosive detonations used to test a concept of explosively emplacing an embankment across a narrow,

steep-walled canyon. The concept envisions the production of the embankment by an explosion centered rather deeply in one canyon wall at about canyon floor level. Both the production of the embankment across the canyon and the refilling of the explosion cavity would be accomplished through the bulking of the in-situ material fractured and displaced by the explosion.

The results of the 1-lb laboratory scale tests in a controlled, compacted sand medium indicate that the concept has merit and that a higher embankment can be produced by this technique than can be produced by a landslide technique. In addition, the Soviets have used direct blasting techniques on an intermediate scale in actual construction operations to form part of such a rockfill embankment for a dam. It is proposed that the directed blasting or bulking technique be investigated further to advance the state-of-the-art of producing a rockfill embankment for a dam or explosively blocking a narrow canyon for other purposes.

TM 67-16

April 1967
Edited and
Abridged
September 1967

NUCLEAR EXCAVATION FEASIBILITY STUDY, CONSTRUCTION OF ROCKFILL EMBANKMENT FOR A DAM

Kleist, E. H.

This study investigates the feasibility of constructing a dam in a narrow, steep-walled canyon by use of nuclear explosives. It emphasizes the conventional engineering and construction activities which would be associated with the construction of a dam by such nuclear excavation techniques.

The report considers construction of a rockfill dam 655 ft in height above the riverbed to form a reservoir. The bulk of the rockfill for the dam would be placed by explosion of a 200-kt nuclear device emplaced in the east canyon wall. The resulting ejecta pile would be shaped into the desired configuration by conventional construction methods. Then the dam would be sealed on the upstream face by an impervious zone protected by suitable filters and riprap. A tunnel in the west abutment would divert the river during the detonation and subsequent construction period. A 24-in. pipe through the tunnel would be the reservoir outlet and the spillway would be a concrete ogee section controlled by four 45-ft by 50-ft tainter gates located in a rock cut in the west abutment.

The nuclear explosion would shatter 24,100,000 yd^3 of in-situ rock and produce an estimated 32,100,000 yd^3 of rockfill. The broken material would be deposited in the canyon and the crater produced by the explosion.

There are 30 inhabitants and 8 permanent dwellings within the area that would be subject to contamination by radioactive fallout; and 125 inhabitants and 30 permanent dwellings within the area subject to damage from air blast or ground shock.

The estimated project cost of construction by a nuclear explosion is $29,630,000 for an irrigation-only project and $35,998,000 for a power-only project. The estimated

annual benefits for an irrigation-only and a power-only project are $748,130 and $988,430, with benefit-to-cost ratios of 0.74 to 1.0 and 0.70 to 1.0, respectively.

Construction of the dam by nuclear excavation would save about $12,000,000 or 29% compared to construction of a comparable dam by conventional methods. However, the design of the dam using nuclear excavation required several broad assumptions that were not supported by experimental data. Detailed test data on these points could affect the dam design and result in an increase or decrease in project cost. It is, therefore, recommended that further tests as proposed in the report be conducted to supply more firm data to be used in evaluating nuclear explosion dam construction.

TM 67-17 September 1967

SITE SELECTION INVESTIGATION FOR A HIGH EXPLOSIVE CRATERING EXPERIMENT IN VARYING TERRAIN

Frandsen, A. D.

The site for a possible varying terrain cratering experiment, at the U. S. Army Yakima Firing Center, was selected after combined office, field and laboratory investigations. Bedrock at the site consists of two highly jointed and fractured basalt flows separated by a nearly horizontal interbed composed of silt, clay, and basalt fragments. The interbed ranges from 2 to 10 ft thick. The upper flow and interbed have been removed from part of the area by erosion. The physical properties of the interbed are distinctly different from those of the basalt flows.

TM 67-18 October 1967

CONCEPTUAL STUDY: DAM CONSTRUCTION IN DIMOND GORGE, WESTERN AUSTRALIA

Holmes, R. S., Kleist, E. H., and Kurtz, M. K. Jr.

This memorandum presents a conceptual analysis of the engineering feasibility of constructing a dam on the Fitzroy River of Northwestern Australia using a nuclear explosion. This concept is based on prior engineering studies and laboratory experiments described in companion reports.

On the basis of current knowledge of site conditions and project requirements for a dam at Dimond Gorge, a tentative design concept and the nuclear explosive yield requirements are developed. The engineering and construction requirements to prepare for the detonation and to complete an operating dam are discussed. In addition, the requirements for a more comprehensive analysis of project feasibility are outlined; these requirements include more specific information on the dam project requirements, more detailed site information, and possibly project modeling and high-explosive site calibration explosions.

TM 67-19 December 1967

CONCEPTS AND TECHNIQUES OF SEISMIC SITE CALIBRATION FOR PROJECT PRE-GONDOLA

Redpath, B. B.

Measurements of intermediate range ground motions and structural response were made during the Pre-GONDOLA cratering experiments at Fort Peck, Montana. The series consisted of 0.5- and 20-ton charges, detonated at various depths of burst, and a 140-ton row charge. All measurements were of particle velocity. An inverse power low equation is used to describe the attenuation of seismic amplitudes with distance. Amplitudes from the single charges decayed as approximately $R^{-2.4}$, and amplitudes from the row charge decayed as $R^{-1.7}$. A dependence of amplitudes on depth of burst exists, and a yield scaling near 0.8 appears to be appropriate. It is suggested that a variation of particle velocity with distance as $R^{-A}e^{-kfR}$, where f is the signal frequency, is a more physically realistic description of attenuation. The data from the 140-ton row charge appear to fit this type of attenuation law, and indicate that A = 0.5, k = 0.015 sec/km. An estimate is made of the near-source variation of peak seismic amplitude with frequency. Predictions for the proposed Pre-GONDOLA III row charge are made for yields of 100 and 140 tons.

TM 67-20 November 1968

PROJECT ANGLEDOZER SITE SELECTION INVESTIGATIONS

Frandsen, A. D. and Fleming, R. W.

This report described the results of site selection investigation activities in connection with Project ANGLEDOZER, a high explosive cratering experiment designed to study the feasibility of using a single point detonation to produce material for a rockfill dam. Three detonation sites were selected near the Chowchilla River north of Madera, California, on the basis of field reconnaissance and an exploratory drilling program. The geology at the sites is characterized by massive biotite granite bedrock overlain by thin, scattered patches of alluvium. The upper part of the granite is weathered to varying degrees and depths. Typically, this weathered rock is soft and friable. Below the weathered zone, the rock, with few exceptions, is very hard and competent. Preliminary laboratory testing, detailed topographic mapping and geological studies indicate that the sites satisfy project criteria.

TM 68-1 February 1968

THE WIND CODE: A COMPUTER PROGRAM FOR CALCULATING AND SUMMARIZING WIND HODOGRAPHS

Bechtell, W. R.

This memorandum describes and explains how to use the WIND code, a computer program which calculates hodographs from raw wind data and summarizes the resulting information. Several possible modifications are suggested which might be useful in future hodograph analyses.

TM 68-2 February 1968

CONCEPTS OF NUCLEAR EXCAVATION

Kleist, E. H.

Chemical explosives have been used for many years in the construction industry. Such explosives generally have been used in excavation projects to break up the material for subsequent removal by mechanical earth-moving equipment. The nuclear explosive, with its vast release of energy, provides an economical means of breaking up the material and ejecting it from an excavation. The following paragraphs have been prepared to give a basic knowledge of nuclear excavation. Potential applications are presented to indicate the range of uses of nuclear explosives as construction tools.

TM 68-3 February 1968

PROJECT PRE-GONDOLA II: PHYSICAL CHARACTERISTICS STUDIES, FORT PECK DAM EMBANKMENT

Kley, R. J.

The studies described in this report were conducted by the U. S. Army Engineer Nuclear Cratering Group (NCG), the U. S. Army Engineer Waterways Experiment Station (WES), and the U. S. Army Engineer District, Omaha.

The pressure relief well monitoring, piezometer pipe monitoring and dam surveys were performed under the direction of Mr. D. C. Beckman, Area Engineer, Fort Peck Area Office, Omaha District. The vibratory seismic measurements were performed under the direction of Mr. R. F. Ballard, Soils Dynamics Branch, WES.

Directors of NCG during the field investigations and preparation of this memorandum were LTC M. K. Kurtz, Jr. and LTC B. C. Hughes.

TM 68-4 February 1968

EFFECTIVE YIELDS FOR EFFECTS PREDICTIONS FOR ROW AND ARRAY EMPLACEMENT OF SURFACE AND BURIED NUCLEAR CHARGES

Day, W. C.

Recommendations are made for determining the effective yield to be used with existing curves and nomographs to make effects predictions for row and array emplacement of surface and buried nuclear charges.

In the upwind or crosswind direction from the surface burst or near surface burst emplacement, the controlling effects appear to be initial nuclear radiation and a missile hazard. Air blast does not appear to be of significance. For the deeper burial case, the controlling effects appear to be the base surge radius and a missile hazard.

Crater dimensions for row charge emplacements should be based upon single charge data plus 10%. No prediction scheme is available for array configurations.

TM 68-5 March 1968

RESULTS OF ARRAY MODELING EXPERIMENT TO PRODUCE FLAT SLOPES USING THE TWO-PASS CONCEPT

Redpath, B. B.

The results of NCG array modeling experiment number SS61 are presented. This experiment was the most recent one in a continuing series of laboratory scale experiments being conducted to investigate methods of producing linear craters with flat side slopes. The experiment used the three-row array two-pass detonation system and achieved side slopes approaching 1 on 6. All charges were 1-lb C-4 center detonated.

TM 68-6 April 1968

SUMMARY OF NUCLEAR CRATER SLOPE STABILITY EMPIRICAL AND ANALYTICAL STUDIES, FY 1963-FY 1968

Earth Sciences Group

This paper summarizes the effort which has been accomplished to date under the U. S. Army Nuclear Cratering Group's ongoing research program to develop the capability to assess the stability of crater slopes resulting from nuclear detonations. The work outlined in the report was accomplished under the technical direction and sponsorship of NCG. The organizations involved in this study effort include:

A. Georgia Institute of Technology and Duke University under the supervision of Dr. A. Vesic

B. Massachusetts Institute of Technology under the supervision of Dr. R. V. Whitman (MIT)

C. U. S. Army Engineer Waterways Experiment Station (WES).

Reports have been or will be published as indicated under each study element.

TM 68-7 April 1968

PRELIMINARY ASSESSMENT OF NUCLEAR CRATER SLOPE STABILITY AS RELATED TO THE INTEROCEANIC CANAL STUDIES

Hughes, B. C.

This paper presents a brief assessment of nuclear crater slope stability as related to the on-going Interoceanic Canal Studies (IOCS). Information is presented on the current and proposed activities of the Corps of Engineers and the Atomic Energy Commission to: (1) develop an understanding of the long-term stability of saturated, weak materials such as the Route 17 Chucunaque Valley clay shales; and (2) develop techniques for using nuclear explosives to produce linear craters with flat slopes in saturated, weak materials. One of the key responsibilities of the Corps of Engineers in the joint AEC/CE nuclear excavation research program is the "development of the requisite data on engineering and construction problems, including erosion and slope stability phenomena." Since its establishment in 1962, the U. S. Army Engineer Nuclear Cratering Group (NCG) has been engaged in empirical and analytical studies to develop an understanding of nuclear crater slope stability and to develop the capability to assess the structural integrity of crater slopes resulting from the underground detonation of nuclear explosives. The U. S. Army Engineer Waterways Experiment Station (WES) has provided significant technical support to NCG in accomplishing these studies. A current status report of the NCG/WES studies program is given in NCG Technical Memorandum 68-6 which is included in this paper as TAB A.

TM 68-8 July 1968

A COMPUTER PROGRAM FOR ANALYZING THE STABILITY OF NUCLEAR CRATER SLOPES

Bechtell, W. R.

This memorandum describes a computer program which may be used to evaluate the stability of a crater slope, assuming either a circular or composite failure surface. The method of slices is used, considering the forces acting between slices, as developed by Bishop and Nonveiller.

TM 68-9 November 1968

PROJECT ZULU II: SUMMARY REPORT OF FLAT-SLOPE ARRAY EXPERIMENTS

Cress, J. P.

This report describes the project ZULU II experiments conducted to develop a design criteria for producing linear craters with flat slopes. The program has culminated in a specific two-pass array system which offers excellent potential for producing linear craters with flat slopes at higher yield levels.

Two detonation schemes were tried in an effort to produce linear craters with flat slopes. In both schemes the array consists of three parallel rows of charges of equal yield. The schemes differ in that (1) all three rows are detonated simultaneously or (2) the two outside rows are detonated first and at a later date the center row is detonated. The most successful experiments have been when the array is detonated in two passes.

The first pass detonation results in two parallel rows and a center mound which is dependent upon the spacing between the two rows. The second pass detonation results in partially filling the two outside rows and the net result is a row crater with flat slopes. The most critical factor to consider in producing linear craters with flat slopes is the depth of burst of the center row of charges. It has been found that when the center row charges are buried too deep the resulting crater has slopes that are benched. When the charges are too shallow the result is a row with a flat bottom and steep side slopes.

The most successful arrays conducted in the test pit to date have resulted in row craters with slopes of about 1 on 5.5.

TM 68-10 July 1968

PRELIMINARY REPORT: NCG PRE-GONDOLA-III SIXTY-FOUR POUND TNT FLAT-SLOPE EXPERIMENTS CONDUCTED AT FORT PECK, MONTANA

Cress, J. P.

As a part of the Nuclear Cratering Group's on-going effort to develop techniques for producing flat-sloped linear craters in weak, saturated media, three multiple-charge, flat-slope array experiments and nine single-charge site calibrations shots, using 64-lb spheres of TNT, were detonated during the period 18 June to 22 July 1968. These experiments were conducted in a weathered clay shale at the Pre-GONDOLA Site, Fort Peck, Montana.

The array experiments were designed on the basis of single-charge crater dimensions in a similar manner to the 1-lb (C-4) arrays in the NCG sand pit facilities at LLL's Site 300. The 64-lb Array #1, which was designed solely on the basis of the Site 300 experiments, did not produce a flat-sloped linear crater. The depths of burst of the charges in the outside rows were too deep; and mounds were formed by the first-pass detonation rather than craters.

Subsequent to detonation of Array #1, a series of nine TNT single-charge site calibration shots were fired to develop cratering characteristics data pertinent to this specific site media. The second and third 64-lb arrays, which were designed on the basis of this cratering characteristics data, did produce flat-sloped linear craters. The row craters produced by the Array #2 detonation had an average side slope of 1 on 5.3 while the slopes of the Array #3 detonation averaged 1 on 4.6. It may be concluded that the basic design criteria developed during the 1-lb (C-4) experiments at the NCG Site 300 test pit are valid for arrays using 64-lb TNT charges in clay shale with the

possible exception of the center-row depths of burst (DOB). It appears that a slightly shallower DOB for the center-row charges in the third array would have resulted in crater side slopes averaging approximately 1 on 6 rather than 1 on 4.6.

TM 68-11 October 1968

SENSITIVITY OF NITROMETHANE AND SURVIVABILITY OF A ONE-TON ALUMINUM SPHERE UNDER HIGH PRESSURE LOADING

Cress, J.P.

In order to pre-emplace the center row of charges in the Pre-GONDOLA III Phase I Alpha Event, both the nitromethane (CH_3NO_2) and its containing sphere must survive the shock generated when the two outside rows are detonated simultaneously.

In an effort to determine if the center row of charges could be pre-emplaced, an experiment was conducted at the University of California Lawrence Livermore Laboratory's Site 300. In the experiment a 45-in.-diameter, 1/8-in. thick aluminum sphere containing nitromethane and a booster charge of C-4 was subjected to a relatively high pressure (2,070 lb/in.^{2}) for a relatively long period of time (350 msec).

The experiment was conducted in two stages. The first stage consisted of several underwater studies in the test pit at Bunker 304 to determine if converging pressure waves are additive and to determine if nitromethane would detonate under high pressure loading. The nitromethane was contained in an 1/8-in.-thick, 3-in.-diameter aluminum sphere. The pressure was generated by 1/4-lb and 1/2-lb charges of C-4. The nitromethane did not detonate under a total pressure of 13,000 lb/in.^{2}, and the pressure pulses converging on the sphere were shown to be additive.

The second stage of the experiment, executed at Bunker 345, was designed to test one of the actual 45-in.-diameter spheres to be used in the Phase I Alpha Array. The test sphere contained 1-ton of nitromethane and was emplaced in a stiff clay medium midway between two 1/2-ton charges of nitromethane which were simultaneously detonated. The spacing between charges was designed to create a pressure on the 1-ton sphere equal to that predicted for a charge in the center row of the Phase I Alpha Array.

The nitromethane did not detonate and the 1-ton sphere was not damaged when the 1/2-ton charges were detonated and a total pressure of 2,070 lb/in.^{2} impinged upon the 1-ton test sphere. It was concluded that the center row of charges in the Pre-GONDOLA III Phase I Alpha Event could be pre-emplaced and would survive the shock produced by the detonation of the two outside rows.

TM 68-12 January 1969

BORHOL: A COMPUTER PROGRAM TO COMPILE GEOLOGICAL ENGINEERING PARAMETERS FROM NX BOREHOLE CAMERA DATA

Furst, G. and Fischer, J. F.

The program described is designed to reduce the data collected from small diameter borings by the NX Borehole Camera. The pictures from the camera yield data on the strike, dip, thickness, and filling of individual fractures. Engineering properties which can be deduced from the data include the structure of the rock (by use of an equal-area net), the distribution of fracture widths, the distribution of fractures with depth, the lineal intercept or block size, and the effective porosity. The code calculates these parameters, making plots and graphs where applicable.

The DD80, a computer controlled display device, and the 7094 IBM computer are used. The DD80 plots the stereonet diagrams and graphs; the 7094 does the calculating, and prints out the tables of values used for the graphs, The Code is written in FORTRAN II.

TM 68-13 November 1968

ANALYSIS OF THE FEASIBILITY OF CHANNEL IMPROVEMENT BY NUCLEAR EXCAVATION AT SERGIUS AND WHITESTONE NARROWS, ALASKA

Mattes, R. W.

This report analyzes the feasibility of using nuclear methods to improve the navigation characteristics of the Sergius and Whitestone Narrows in Alaska. It is concluded that while nuclear explosives could be used to widen navigation channels at Sergius and Whitestone Narrows, the project costs for such an undertaking would be over a factor of four greater than the costs for a conventional excavation method. The most economical alignments for nuclear excavation are identical with those recommended for the conventional project by the Alaska Engineer District. A major cost liability of the nuclear excavation technique for this project is the postshot dredging required to clear debris from the channels. Safety analyses show ground shock to be the greatest potential damaging effect for area industries, while the radiation levels in the lip areas may cause a significant delay in the start of channel cleanup work.

TM 68-14 November 1968

ANALYSIS OF VESIC CRATER MODELING EXPERIMENTS

Nelson, D. L. and Taylor, T. S. III

A series of small-scale cratering experiments was conducted in a simulated "half-space" for the purpose of observing the crater-formation process. Hemispherical charges of lead azide weighing 0.42 g, 0.84 g and 1.68 g were fired against the Plexiglas wall of a sand-filled box through which the cratering process could be observed in

cross section. A group of shots was fired under level terrain to study the effects of charge size and depth of burst. Another group was fired under a variety of slopes, ridges and valleys to study the effects of surface terrain. A third group of shots was a study of the formation of linear craters using rows of charges.

All shots were photographed by a high-speed motion picture camera. This report consists of a qualitative description of the dynamic crater formation process observed from the high-speed photography and a series of postshot crater profiles for each shot.

TM 68-15 January 1969

AN ANALYSIS OF THE GRID PHOTOGRAPHY TECHNIQUE AS A MEANS OF DETERMINING THE SIZE DISTRIBUTION OF CRATER FALLBACK AND EJECTA

Anderson, B. D. II

The purpose of this memorandum is to analyze the validity of the "grid photography technique" as a means of determining the block size distribution of crater ejecta and fallback materials. Current methods of determining particle size distribution are summarized and pertinent factors affecting the accuracy of methods of size distribution analysis are discussed. A method of determining the particle size distribution by size and weight without the use of sieving and weighing or grid photography is recommended.

TM 68-16 January 1969

PRELIMINARY ASSESSMENT OF THE POSTSHOT ENGINEERING AND CONSTRUCTION REQUIREMENTS FOR THE CAPE KERAUDREN PORT DEVELOPMENT PROJECT

Johnson, J. D.

This report presents a preliminary assessment of the postshot engineering and construction tasks required to convert a linear crater produced by nuclear explosives into a useful harbor at Keraudren Bay, Australia. This analysis was made in conjunction with the Lawrence Livermore Laboratory as part of an overall conceptual study of the feasibility of using nuclear explosives to excavate a harbor.

It is concluded that, based on the available geologic and environmental information, it is feasible to construct a useful harbor facility at any of the proposed nuclear crater locations. The current analysis indicates that the postshot engineering and construction costs are minimized when the harbor facility is located close to the shoreline.

TM 69-1 January 1969

PRELIMINARY ESTIMATION OF THE POSTSHOT INTERVAL REQUIRED FOR RADIONUCLIDE CONCENTRATION IN FAMILY COW MILK TO DECAY TO ACCEPTABLE LEVELS

Sowers, A. E.

This report presents a method by which a rapid preliminary estimate can be made of the interval during which the consumption of milk from a cow grazing on pastureland contaminated by a nuclear cratering event may have to be interrupted. A discussion of the approach used in developing the predictive method is presented. The results of this approach show that the child thyroid dose from I-131 is the critical organ-isotope combination. In order to predict the interval of the temporary interruption of milk consumption, the method is based on this critical organ-isotope combination and assumes the availability of (1) a prediction of the H+1 hr exposure rates in the downwind fallout area, and (2) knowledge of the season of the year in which the detonation is to take place. Calculations based on a 100-kt Plowshare nuclear explosive detonated at optimum depth of burst are made to illustrate the method.

TM 69-3 February 1970

PROJECT ZULU II: HARBOR MODELING STUDY

Fitchett, D. J.

This report presents the results of a series of laboratory-scale cratering experiments which were designed to model a nuclear harbor excavation in shallow water adjacent to a shore line. The chemical explosive experiments evaluated quantitatively the size of the end lip of a row crater as a function of the end charge yield.

The experimental results indicate that if the last charge in the row is about one-tenth the yield of the other charges, then the lip height at the end is approximately one-half of that for a row of equal charges. Charge weights are scaled to the kiloton range for application to nuclear excavated harbor proposals.

TM 69-5 April 1970

A METHOD FOR PREDICTING FINAL RUBBLE SIZE IN EXPLOSIVE EXCAVATIONS

Fischer, J. F.

The lineal joint intercept method uses the spacings between successive joints in boreholes to calculate in situ block size distributions. Two dimensional models indicate that in situations with random spacings between the joints the method gives a good approximation to the block size distribution. The in situ block size distribution at a particular cratering site can be compared with the postshot rubble size and the relationship between the two size distributions determined.

To make the comparison, the intercept data must first be converted into a distribution which is similar to sieved rubble curves. The following equation uses the intercept data to yield a size distribution by volume (weight if density is constant):

$$\%V_j = \frac{\sum_i l_{ij}}{\sum_j \sum_i l_{ij}}$$

where

V_j = the volume (weight) of blocks in size class j

l_{ij} = the length of the ith intercept; occurs in class j

The rubble grain size is equal to or smaller than the in situ block size, due to crushing by the detonation. Rubble from silicic volcanic rocks seems to have little or no crushing in the sizes greater than 0.1 ft. Rubble from basalt undergoes considerable crushing, with the finer sizes being the more highly crushed. Rubble mounds in the same basalt show less crushing, indicating that the fine material about craters is derived from highly crushed basalt originally near the shot point.

TM 69-6 January 1970

GENERAL SITE SELECTION STUDY

Frandsen, A. D.

This report describes a general site selection study undertaken during the period 1964-1967. The purpose of the study was to catalog potential cratering experiment sites. The study was expanded from an initial investigation of military bases to encompass all potential high explosive cratering experiment sites in the Continental United States. This report describes the study and the information developed, and indicates the present status. The appendixes include data collected and cross-references to the base maps used in the study.

TM 69-7 May 1969

PREDICTED EXPOSURE RATES WITHIN THE NUCLEAR CRATER AND LIP AREA

Tami, T. M.

This report presents an analytical technique for estimating the gamma radiation exposure rate in the crater and lip area resulting from the radioactive decay of gamma emitting radionuclides contained in the ejecta and fallback of large nuclear craters.

The model assumes a uniform distribution of the radioactivity in the ejecta and fallback. Contributions to the exposure rate from fission products and from each species of induced radionuclide are treated separately. By proceeding in this manner the exposure rate can be predicted as a function of time after the detonation. A means of empirically adjusting the predicted exposure rate to account for changes in the mixing and venting processes resulting from detonations at varying depths of burst is also included.

Conservative estimates of the exposure rate as a function of time after the detonation are given for five nuclear explosive yields (10, 100, 500 kt; and 1 and 10 Mt). These estimates show that for cratering detonations at optimum depth of burst reentry times decrease as explosive yield increases.

TM 69-9 August 1970

ESTIMATING THE INTERNAL RADIATION DOSE TO MAN VIA MAJOR ECOLOGICAL PATHWAYS FOR PLOWSHARE NUCLEAR CRATERING EVENTS

Sowers, A. E., Corsiglia, L. J., and Vollmerhausen, R.

This report develops a method to estimate the total internal radiation exposure to both the whole body and the most sensitive body organ from each radionuclide released to the biosphere by a Plowshare nuclear cratering event. The method takes into account the variabilities and uncertainties in the various ecological processes. It is concluded that, for unfractionated fallout, the areal extent and time duration of actions required to prevent excessive exposure to man can be estimated rapidly from a prediction of the H+1 hour iso-exposure rate contours. The accuracy of the predictions should be sufficient for radiological safety analyses for project feasibility studies.

TM 69-11 July 1970

SUMMARY OF EXPLOSIVE CRATERING PERFORMANCE TESTS CONDUCTED AT SITE 300 DURING 1969

Bourque, R. F.

The explosives test program of Site 300 was conducted during the summer of 1969 to evaluate the cratering performance of a number of commercially available chemical explosives with emphasis on those containing ammonium nitrate. While many of the explosives tested have been widely used in mining and quarrying operations, little information was available concerning their cratering effectiveness. The aim of the test program was to fill this gap in the available data and determine those explosives which, for a given application, maximize the ratio of apparent crater volume to total cost. This program is open-ended; that is, new explosives are tested as they become available.

TM 69-12 January 1970

LUNAR EXCAVATION WITH BURIED EXPLOSIVES

Bourque, R. F.

True crater formation sprung volumes, and shaped charge penetrations are shown to be independent of gravity in reasonably competent media. Consequently geometric (cube root) scaling prevails for all three phenomena.

The effect of the reduced lunar gravitational field on the ballistics of particles propelled above the surface by a buried explosion and the subsequent increased lunar apparent crater volume as compared to the terrestrial case is dealt with analytically by assuming that the adjusted postshot distribution of fallback and ejecta follows a normal curve. It is shown that, even for a nearly-contained terrestrial cratering event, the lunar counterpart produces negligible fallback and consequently cube root scaling of lunar apparent craters is appropriate.

Two example problems are presented to illustrate typical payload requirements for lunar excavation by means of explosives.

TM 70-1 March 1970

ANALYSIS AND REEVALUATION OF BULKING FACTORS

Frandsen, A. D.

The memorandum discusses the factors which effect the bulking factor of the fallback and ejecta materials resulting from cratering experiments.

A procedure is outlined for computing in situ densities for input to bulking factor determinations. It is shown that simple averaging of laboratory densities given erroneously low bulking factors. Assuming either a truncated cone or paraboloid shape for the true crater and computing an average weighted density gives more accurate values in a layered medium.

Previously published bulking factors have been recalculated. This results in lower bulking factors which are more in line with conventional blasting experience.

TM 70-3 January 1971

CHEMICAL EXPLOSIVE EXCAVATION STATE-OF-THE-ART

Leu, R. K.

This report summarizes the current chemical explosive technology related to surface and underground excavation for construction and mining operations. It was prepared as reference material for a technical report (NCG TR-25) entitled "Study of Explosives for Lunar Application." Therefore, emphasis is placed on those uses of explosives which may have application in lunar base construction and lunar operations.

The report summarizes explosive excavation principles, characteristics of explosives, charge emplacement and firing, and safety considerations and discusses blasting techniques for surface and underground excavation. The detonation process is described, and the extent of disturbance to the surrounding medium with varying depth of burst is discussed. Multiple charge and directed blasting techniques are summarized. The various characteristics of explosives are assessed from the explosive selection standpoint. The roles of rotary, percussive, rotary-percussive and jet-piercing drills in blasting and cratering operations are described, and the potential use of shaped charges and hole springing for emplacement construction is summarized. Common methods of loading, stemming, priming, and firing are presented. The phenomenology of ground shock, airblast, missiles (throwout), and associated safety considerations and damage criteria are discussed. Typical drilling and firing patterns in bench, coyote, secondary, and controlled blasting in quarrying and surface mining operations, and those used in ditching, tunnel driving and shaft sinking are discussed. Cratering is presented as a special method of explosive excavation, and general design criteria and examples of potential applications are provided. In addition, the use of explosives in seismic surveying is summarized.

TM 70-4 January 1971

EXPLOSIVE EXCAVATION ON THE MOON: THE LUNAR SURFACE, LUNAR EXPLOSIVES AND EMPLACEMENT, TERRESTRIAL MODELING TECHNIQUES, AND SEISMIC, BLAST, AND EJECTA EFFECTS

Bourque, R. F.

This report addresses special problems in explosive excavation which are created by the remoteness of the moon and the severe lunar environment.

Lunar explosives are selected on the basis of safety, compatibility with the lunar environment, and energy density. Five explosives are suggested. One, which consists of aluminum powder and liquid oxygen, is recommended for large cratering charges. Two aluminum-high explosive mixtures are selected for quarrying. Finally, one aluminum-high explosive mixture and one magnesium-high explosive mixture are selected for small cratering charges.

Five techniques for drilling holes on the moon are presented: (1) conventional, (2) shaped charges, (3) rocket propelled penetrators, (4) concentrated solar energy, and (5) laser. To enlarge the necessarily small drill holes to accommodate cratering charges, emphasis is placed on linear springing.

Rather than perform calibration cratering shots on the moon, it is recommended that proposed lunar excavation projects be modeled on earth. Two methods of terrestrial modeling are presented: one-sixth scale and full scale. Both require a terrestrial analog of the lunar surface. All important similarity requirements, including gravity, are satisfied by a terrestrial model with 1/6 the burial depth and 1/216 the charge mass of the lunar counterpart. Fullscale models are shown to accurately

reproduce lunar true craters. Lunar apparent crater dimensions are then determined by adjusting the terrestrial fallback volume to account for differences in gravity. It is shown that lunar apparent crater volumes nearly equal terrestrial true crater volumes and therefore cube root scaling of lunar apparent crater dimensions is appropriate.

Blast overpressures are generated by the free expansion of the explosion gases into the lunar vacuum. It is shown that, unlike terrestrial blast overpressures which decay inversely with range, close-in lunar overpressures decay with the range cubed and therefore pose no special hazard.

Ejecta ranges in lunar explosive excavation could be a problem except that the size of the particles ejected beyond several kilometers is very small and their number density is low. Also, the charges can be buried deeper than the calculated optimum with little loss in performance in order to greatly reduce ejecta range.

TM 70-5 February 1971

CONCEPTUAL LUNAR APPLICATIONS OF CHEMICAL EXPLOSIVES

Thorne, G. E.

This report presents suggested applications and engineering considerations and criteria for the use of chemical explosives in lunar operations. It was prepared as reference material for a technical report (NCG TR-25) entitled "Study of Explosives for Lunar Application."

The report suggests a number of possible applications of explosives in lunar operations. Explosives in these operations may allow the construction or implementation of facilities at a more rapid rate and with savings of time and manpower over mechanical methods of lunar construction.

Design criteria and considerations are developed for the use of explosives in lunar operations. Methods of explosive excavation design, material characteristics, and safety considerations are discussed. Methods of explosive emplacement, hole drilling, and material movement are presented.

Six example designs that demonstrate the types of applications to which explosive energy might be put to use are presented: (1) row charge shelter burial, (2) single crater power reactor burial, (3) underground storage cavity, (4) overburden removal, (5) quarry operation, and (6) underground mining or ore shattering.

The report concludes that research and development is necessary in several areas before a lunar explosive excavation technology is established. Improved emplacement hole construction capabilities and increases in explosive energy releases are of prime importance in the research and development effort.

TM 70-6 August 1970

TRAINING FOR CHEMICAL EXPLOSIVES EMPLOYMENT FOR LUNAR APPLICATIONS

Sprague, K. E.

This report presents (1) a study of tasks involved in the utilization of chemical explosives in the lunar environment, (2) defines the training required to prepare a worker to accomplish these tasks, and (3) assesses the Department of the Army's existing capability to accomplish this training.

The task analysis is based on material presented in TM's 70-3, 70-4, and 70-5. The tasks are categorized into Phase I, II, or III by sequence of initial implementation and by difficulty of execution. The current NASA astronaut selection and training program could provide candidates capable of being trained to use explosives including emplacement of a lunar shelter.

The training required would be similar in scope to conventional explosives training by Department of the Army agencies, modified to include the constraints of the lunar environment and changes in explosives or emplacement systems. The training method would include the dynamic rate of progress subjective feedback which is characteristic of current astronaut training. Additional facilities would be required to simulate lunar environmental effects.

TM 70-7 April 1971

ANALYSIS OF HYDROLOGIC TRANSPORT OF TRITIUM

Little, W. M.

A hazard associated with the use of nuclear explosives in construction is the radioactive materials which remain after detonation of the device. One of these materials is tritium. Tritium, in the form of tritiated water, is extremely mobile in the hydrologic cycle. In order to assess the hazard of tritium exposure, it will be necessary to adequately predict the movement of tritium in the hydrologic cycle.

This memorandum presents: (1) a logical procedure for assessing the overall tritium contamination hazard; (2) some current methods and models for predicting tritium movement; and (3) an identification of current gaps in knowledge and/or capabilities.

A literature search was performed, seeking methods of predicting hydrologic transport of tritium, and observational evidence to support the reliability of such methods. Insufficient experimental or operational evidence was found to satisfactorily demonstrate the reliability of any method.

TM 70-8 February 1971

RAINFALL LEACHING MODEL FOR FALLOUT TRITIUM: THE RAIN CODE

Little, W. M.

One aspect of fallout tritium movement in the hydrologic cycle is leaching from the soil column by rainfall. A climatological and activity balance model is proposed to predict rainfall leaching rates. A computer program, the RAIN Code, is presented to implement the model. Data inputs are average monthly potential evapotranspiration rates, average monthly rainfall depths, and soil moisture capacity parameters. Outputs are monthly terms and annual summaries of the water and activity balances.

TM 70-11 August 1971

SUMMARY OF UNDERWATER CRATERING TESTS CONDUCTED AT SITE 300 DURING 1970

Sakai, K. T. and Bourque, R. F.

Laboratory tests were conducted to determine the effect of a water overburden on cratering performance in sand. The objectives were to determine the parameters which describe the effect of the water overburden on the final crater configuration and to develop a relationship for the maximum water wave generated by the explosion. Spherical 1-lb charges of composition C-4 were detonated at depths of burial in the medium ranging from 0 to 24 in. with a varying water overburden of 0 to 12 in. Crater dimensions and maximum wave height data were analyzed empirically with the Buckingham Pi dimensional analysis technique. The data indicate that crater dimensions appear to be sensitive to small changes in water overburden (d) for a constant depth of burial in the medium (d_m) for $0 < d/d_m < 0.6$. The most sensitive region is $0 < d/d_m < 0.2$, where the crater radius increases abruptly, the crater depth decreases sharply, and the lip height decreases as the water depth is increased. The parameters which scale the maximum wave height, H, are Hr/d^2 and $Z\,d^3/W$, where r is the radial distance from the explosive, Z is the lithostatic head on the explosive charge, and W is the weight of the charge.

TM 70-12 March 1971

FEASIBILITY OF CONSTRUCTING A MILITARY HARBOR USING NUCLEAR EXPLOSIVES

Warden, F. F. and Tami, T. M.

This report compares nuclear and conventional excavation techniques as they may be applied in the construction of a military harbor. The hypothetical location of the harbor was chosen to be Ka Lae, the southern tip of the Island of Hawaii, and is called South Point Harbor. The conceptual analysis of the nuclearly excavated harbor is based primarily upon the experimental results of the nuclear cratering event, BUGGY.

In this study, both ADM and PLOWSHARE nuclear explosives are considered with particular emphasis on the safety considerations inherent in their use. It is shown that a substantial savings in construction time exists only when the Plowshare explosives are considered. This leads to the conclusion that a new ADM family of explosives in a low-fission, suppressed-radiation version would have significant advantage for expedient military construction applications.

TM 70-13 April 1971

A METHOD FOR ESTIMATING THE BULKING FACTOR OF RUBBLE IN EXPLOSIVE EXCAVATION

Struckel, J. C.

The bulking factor, a ratio of preshot in situ density to postshot bulk density, is a valuable parameter in determining postshot porosities of rubble in an explosive excavation, balancing cuts and fills, and as a conversion factor for estimating earth and rock moving production rates.

This memorandum discusses a new simplified method for estimating the bulking factor of rubble produced by explosive excavations. It is limited to craters from charges placed at optimum depth of burial but is acceptable for use in all types of media with the exception of clay shale.

The method requires only two variables, apparent crater volume and volume of the apparent lip, to obtain reliable bulking factors. The bulking factors obtained by this method compare favorably with the bulking factors obtained previously by costly field investigations.

TM 70-14 March 1971

A REVIEW OF MATERIAL ON PREDICTING UNDERWATER SHOCK WAVE DYNAMICS AND SAFE DISTANCES FOR UNDERWATER SWIMMERS

Corsiglia, L. J.

This report presents the results of a literature search for data indicating the effects of underwater shock on man and marine life. The original objective, a method which would permit prediction of underwater shock parameters from cratering detonations overlain with water, was not achieved, nor were data found which indicate the underwater shock parameter that may be tolerated by man and marine life. The report does present material important for the prediction of peak pressure and impulse resulting from underwater detonations. "Free water" predictions provide reliable, conservative estimates for deep water configurations in which boundary and surface reflections are present. Peak pressure attenuates more rapidly for a shallow water detonation than for a deep water detonation, and it is also more difficult to predict for the shallow water case than for the deep water case. The safety standard of 5 $lb/in.^2$, the threshold for

rupturing eardrums in air, is used to estimate safe distance from a 100,000-lb detonation for underwater personnel. A preliminary investigation of the relationship between peak pressure and duration of the pulse in producing injuries is made.

TM 70-15 October 1970

USER'S MANUAL FOR CRATER DATA: A COMPUTER CODE FOR ANALYZING EXPERIMENTAL CRATERING TESTS

Bourque, R. F.

This manual is intended for the user of the CRATER DATA code. CRATER DATA is a computer program which has been developed to facilitate analysis of single-charge experimental cratering data by plotting these data in a variety of ways. In addition to plotting the shots, a quadratic least squares fit is generated within each shot group.

In this manual, a "shot" refers to a single-charge cratering event, a "shot group" refers to a set of shots in which some experimental variable, other than DOB or charge weight, is held constant. Typical experimental variables are:

1. charge l/d
2. depth of water overburden
3. type explosive
4. type medium
5. scaling exponent.

A "shot group set" refers to a collection of shot groups in which the experimental variable manipulated from one shot group to the next is the same. A "test series" is a completely self-contained test program such as Project TRINIDAD or Project TRENCHER. Since more than one experimental variable may be manipulated during a test series, the subdivision "shot group set" is included.

Input and output of the CRATER DATA code are described explicitly in this manual. The detailed workings of the code are not discussed in depth. However, a FORTRAN listing appears in Appendix A, the manner in which volumes are calculated is discussed in Appendix B, and the adjustment for bulking is presented in Appendix C.

TM 71-1 February 1972

COST EXPERIENCE OF EXPLOSIVE EXCAVATION EXPERIMENTS

Wnuk, W. J.

A study of the cost experiences of explosive excavation from the mid-1960's to the present has revealed that, as a general trend, the near future will offer prices of about \$1.00-\$2.00/yd^3 for explosively-excavated material. The average construction and support cost per pound of explosive has been about 60¢. This figure is an average estimate of all the construction and support required to accomplish a project on a per

unit explosive basis, exclusive of the cost of the explosive. Recent trends in design and the use of longer cylindrical charges has reduced the average construction and support cost per pound of blasting agent to approximately 20 to 30¢, substantially lower than the 60¢ average for all projects to date. The amount of explosive (TNT equivalent) required per cubic yard of excavated material is about 2 to 6 lb/yd^3. Additional unit cost reduction for explosive excavation is contingent upon improvement in the design and detonation techniques utilized in explosive excavation or upon the development of an inexpensive technique of producing a cavity to contain the bulk-type blasting agent.

The results of this study must be interpreted carefully. The majority of explosive excavations conducted to date have been designed both to excavate material and provide experimental data. Numerous scientific "add ons," readily identifiable in these experiments, complicate design and dramatically escalate execution costs. In addition, most of the projects have been small in a relative sense which increases prices. Also, special design considerations or site conditions unique to a particular project could effect the cost significantly. In development of this cost history, particular emphasis is placed upon determination of costs related to the project execution and deletion of scientific experimentation costs.

TM 71-2 December 1971

EXPLOSIVE CAVITY CONSTRUCTION BY DRILLING AND UNDERREAMING

Struckel, J. C. and Wnuk, W. J.

This report describes the state-of-the-art methods for and cost estimating procedures considered applicable to large-diameter subsurface boring, specifically mechanical drilling for explosive excavation. The report is concerned with diameters of 12 to 72 in. and depths to 100 ft.

The four mechanical drilling techniques considered applicable are: (1) churn drilling, (2) augering, (3) core or calyx drilling, and (4) fullbore rotary drilling with special emphasis on underreaming. Of these, the most applicable and economical for explosive cavity construction appears to be augering in weak rock or soil and possibly the underreaming technique of rotary drilling for some intermediate and high-strength materials. Where underreaming is not applicable, large-diameter rotary drilling seems preferable.

Cost analysis for explosive cavity construction is complex and depends on a number of variables such as drilling rate, rotary speed, bit weight, torque, horsepower, and drill bits. Rock drillability, diameter, and depth requirements have the greatest effect on drilling costs. In general, total drilling costs appear to increase linearly with depth while increasing more rapidly with increasing increments in diameter and hardness. Cost information contained in this report is for preliminary planning only.

TM 71-3 September 1971

MEDIA CLASSIFICATION FOR EXPLOSIVE EXCAVATION

Gates, R. H. and Gardner, C. E.

A media classification system is developed for use with explosive excavation. The system expands the two categories of excavation used by the Corps of Engineers; i.e., common (which does not require conventional systematic drilling and blasting) and rock (which does). Rock materials are further classified as weak, intermediate-strength, and high-strength rock. Refinements are provided by adding lithology, soil classification, geologic structure, degree of saturation, joint spacing, and thickness of bedding. A secondary classification provides specific property values which further define the medium. The system is used to classify the media at all known cratering events.

TM 71-4 December 1971

WEDGE SLOPE STABILITY ANALYSIS OF EXPLOSIVE EXCAVATIONS

Zehrback, B. E.

The slope stability of crater slopes has been under investigation for some time. The stability of fallback slopes has been investigated and compared with natural rubble and talus slopes. However, the influence of fallback on the overall factor of safety of a crater slope has not been investigated.

The memorandum presents the results of a parameter study done on the factor of safety of a mass sliding on a plane of weakness in the rupture and intact zones of an explosively-produced crater. The study analyzes the buttressing effect of the fallback material and its influence on the factor of safety of the sliding mass.

The results show that the fallback of the crater does increase the stability of the slopes. The amound of increase in the factor of safety of the plane of weakness depends on the geometry and strength parameters. An increase of over 100% in the factor of safety has been computed.

TM 71-5 May 1971

GROUNDWATER AND PIEZOMETRIC RECORDS FOR PRE-GONDOLA CRATERS

Shackelford, T. J.

This report summarizes the groundwater data collected for Project Pre-GONDOLA. One aspect of the groundwater investigations, the piezometer program, is discussed in detail. Supporting data are recorded in the Appendix.

TM 71-6 January 1972

RESULTS OF CYLINDRICAL CHARGE TESTS CONDUCTED AT SITE 300, 1970

Gilson, D. R. and Mays, L. W.

A program of cylindrical-charge cratering experiments was conducted to evaluate the effects on crater dimensions caused by changes in charge geometry (length-to-diameter ratio, or l/d), point of detonation, and the placement of the charge relative to the optimum depth of burial for a spherical charge of equal weight.

Tests were conducted using 4- and 12-lb charges of composition C-4 in sand. For the 4-lb tests the initiation point was maintained at the center and the position of the charge was varied with respect to the optimum depth of burial (DOB). For the 12-lb series the position of the charge was fixed and the initiation point was varied. The results of the 12-lb series are questionable because the charges were buried too deeply with respect to the optimum depth.

Craters produced by 4-lb charges with large l/d ratios were slightly narrower and deeper than the craters produced by charges with small l/d ratios. For center- and bottom-initiated 12-lb charges, the crater radius decreased somewhat with increasing l/d ratios while depth remained essentially constant, resulting in a slight reduction in crater volume. However, in the case of top-initiated 12-lb charges both the crater radius and crater depth increased with increasing l/d ratio, resulting in a substantial increase in cratering performance.

No definite conclusions could be made concerning the positioning of the charges relative to the optimum DOB of a charge with an l/d ratio of 1. However, for small l/d ratios the maximum crater radius and depth occur when the center of the charge is positioned at the optimum DOB. For large l/d ratios, the maximum crater radius occurs when the lower 1/3 point of the charge is positioned at the optimum DOB, and the maximum depth is achieved when the bottom of the charge is positioned at the optimum DOB.

TM 71-7 February 1971

DESIGN AND ANALYSIS OF SPHERICAL ALUMINUM CONTAINERS USED IN THE MIDDLE COURSE CRATERING EXPERIMENTS

Warden, F. F.

This paper presents the analyses leading to the design of the spherical containers and the support apparatus used in the airburst portion of the DASA-sponsored MIDDLE COURSE Experiments which were conducted in conjunction with the single-charge cratering series of Project TRINIDAD. In considering the structural integrity of the containers, both stress and displacement analyses were employed. A classical approach was used in the stress analysis and a finite element approach was used in the displacement analysis. It was found that a hemispherically placed support ring presented the most favorable means of holding the suspended containers in place. The recommended support apparatus that resulted from the analysis was successfully employed.

TM 71-8 March 1972

TREE DAMAGE FROM THE TRINIDAD CRATERING EXPERIMENTS C-1, C-2, AND C-3

Snell, C. M.

Environmental damage is potentially an important factor in the application of explosive cratering techniques to large-scale civil works construction projects. Previous studies have not specifically considered destruction to the natural environment due to the effects of underground explosions. This report investigates the effects on trees caused by three moderate yield (5 to 7 ton) row-charge cratering experiments conducted near Trinidad (Las Animas County), Colorado. These experiments all utilized rows of individual aluminized ammonium nitrate slurry charges emplaced in sandstone near the optimum burial depth for cratering. Effects of the three detonations on trees in the adjacent sparse pinyon and juniper forest were studied. Perpendicular distances from the row axes to various tree damage levels were measured, and these damage levels were correlated with possible environmental effects of the detonations. The results indicate that damage and tree kill occurred at distances where the levels of airblast overpressure and impulse and peak ground motion were quite low. Other mechanisms which may be involved in creating the observed tree damage are suggested. Further studies are required to isolate the critical mechanism.

TM 71-9 January 1972

UNDERWATER EXPLOSIVE EXCAVATION MODELING TESTS

Kleist, E. H. and Florey, M. R.

Laboratory tests were conducted to determine the effect of water overburden on explosive excavation in hard rock. The objectives were to determine the effect of a water overburden on crater dimensions and peak surface-ground-zero mound velocity. The impetus for this work was the need to verify design concepts used for the SERGIUS NARROWS underwater excavation project. The design principles, however, are applicable to underwater rock excavation projects in general.

Spherical 1-lb charges of Composition C-4 were detonated in concrete at depths of burial from 6 to 24 in. without water overburden in order to determine the "dry-land" cratering characteristics of the test medium. Identical charges were detonated with a water depth varying from 3 to 24 in. while the depth of burial in the concrete varied from 3 to 15 in. Two array experiments were designed on the basis of the single-charge cratering data to investigate charge spacing and time delays, with the effects of the water overburden taken into account.

The results verified the design concept for removing the rock ledges on the SERGIUS NARROWS project by directed blasting. The analysis of the effect of water overburden is believed to be generally applicable to directed blasting and to underwater cratering in rock.

TM 71-10 March 1972

PROJECT MINI-MOUND

Shackelford, T. J.

Project MINI-MOUND was an experiment conducted near Trinidad, Colorado, to investigate the use of mounding detonations as an alternative to throw-out cratering for through-cut excavations. The primary objectives of Project MINI-MOUND were related to mounding row design, controlling the fracturing of the side slope region beyond the true crater boundary by explosively creating a buffer zone, and ground motions generated by mounding detonations.

Project MINI-MOUND was conducted in two phases; both phases consisting of test panel studies and two single-row mounding detonations. The presplit-buffer-zone concept of controlled blasting was applied at Rows 1B and 2B.

Results of Project MINI-MOUND revealed that mounding detonations can provide a large volume of readily usable broken rock. In intermediate strength rock the fracturing of the side slope region beyond the true crater boundary can be controlled by using an explosively-created buffer zone and presplit line in conjunction with the main charge detonation. Due to instrument troubles, the ability of the buffer zone to attenuate the seismic shear waves generated by the detonation of the main row of charges was not documented.

TM 71-11 August 1967

A STUDY OF EMPLACEMENT CONSTRUCTION TECHNIQUES FOR THE EXPLOSIVE EXCAVATION OF SERGIUS NARROWS

Sprague, K. E.

This study of emplacement construction techniques and costs was performed to determine the feasibility of removing the two rock shoals in Sergius Narrows, Alaska, through the use of explosive energy to fragment the rock and cast it into deep water by directed blasting techniques.

Because of the paucity of published information on drilling and blasting operation in a tidal environment, information on equipment capabilities and costs was solicited from governmental agencies, trade groups, and individual manufacturers and contractors.

To select the best system for constructing the emplacement holes for the large explosive charges required, the following large-diameter hole drilling methods were reviewed and correlated with responses received from contractors: calyx drilling, churn drilling, auger drilling, rotary drilling and percussive drilling. Rotary drilling was found to be the most versatile and the most widely used in offshore drilling operation. Drilling rates for a 36-in.-diameter hole could range from 5 to 15 ft/hr. Additional economies of time might result if the rotary drilling techniques of underreaming or surface raise drilling could be used.

Similarly, a review of offshore support structures for drilling operations was performed. The moveable jackup platform was found to be the most versatile, to have the largest availability, and to have the most cost information available. The modular system jackup platform was selected for cost estimates because an optimum configuration to match the drilling and the marine environment can easily be assembled at the job site.

An analysis of drilling rates, repositioning times, hole depths and tide cycles indicates that the emplacement holes could be completed at a two hole per day rate.

TM 71-12 December 1971
EXPLOSIVE EXCAVATION TEST FACILITY, SITE 300
Wnuk, W. J.

This report discusses the facilities available to the U. S. Army Engineer Explosive Excavation Research Laboratory (formerly the U. S. Army Engineer Nuclear Cratering Group) to conduct chemical explosive cratering experiments on a laboratory scale. It also discusses the procedures utilized in the operation of this facility. Experiments have been conducted on a laboratory scale at Site 300 as a continuous research effort since 1965. Among the major objectives of these experiments have been the investigation of the geometry of craters produced by single- and multiple-charge detonations in various media and in complex terrain conditions, the determination of ejecta distribution from cratering detonations, and the study of the phenomenology of crater formation.

The Site 300 test facility has consistently demonstrated its value as a rapid and economical tool for the study of cratering phenomenology under controlled conditions. The facility has also proven to be extremely useful for modeling large-scale explosive excavation concepts.

The Engineering and Construction Division is responsible for the scheduling and execution of work at Site 300. The overall responsibility for Site 300 operations, however, rests with the University of California, Lawrence Livermore Laboratory, Livermore, California.

TM 71-16 (SRD) January 1972
PREDICTION OF FALLOUT FROM BURIED NUCLEAR DEVICES (U)
Snell, C. M.

A two-cloud scaling model for predicting fallout from underground nuclear detonations is presented. This model successfully circumvents some of the inadequacies of previous empirical prediction techniques. The physical derivation of the model is discussed in detail, and the calibration of model predictions using observed test results is briefly described. The model serves as a basis for two different prediction techniques, the Simplified method and the Detailed method. Both techniques use as input data the device yield, fission yield/total yield ratio, emplacement depth, emplacement

medium, and the vertical wind hodograph. The Simplified method can, however, be applied without extensive wind data if desired. Both methods can be applied using only hand calculations; the quantity predicted is the (H+1) hour exposure rate, and predictions are valid over a great range of exposure rates.

Appendix A of this report compares actual scaling model predictions to observed fallout patterns and to Army method TM 3-210 predictions. The differences between various prediction schemes are discussed. Inclosure 1 to Appendix A also summarizes time-dependent exposure rates and cumulative dose calculations for fission product fallout.

EERL TR-22 presents convenient step-by-step procedures for performing Simplified and Detailed method fallout predictions ((H+1) hour exposure rates). Other fallout parameters of interest may also be predicted if desired.

Appendix B briefly reviews the data and techniques used to predict cloud dimensions for buried detonations. Both base cloud and main cloud sizes are discussed.

Appendix C summarizes the limited fallout information available for low-yield nuclear near-surface bursts, and gives plausibility arguments for the prediction of fallout from low-yield buried detonations.

TM 71-17 April 1972

SHOCK WAVE INTERACTION AND NEAR-SURFACE CAVITATION, PROJECT TUGBOAT

Snell, C. M.

The TUGBOAT IIC experiment, part of a project to excavate a small-boat harbor in coral with chemical explosives, consisted of a square array of four 10-ton charges detonated at a depth of 40 ft under seawater and saturated coral. This event produced a complex shock wave interaction near the water surface, visible as a series of nulls and reinforcements in the intense near-surface cavitation pattern between the various charges. These features were clearly seen on several successive frames of a 16-mm movie taken from a hilicopter above the detonation, but could not be detected in ground-level photographs. A suggested explanation of the pattern features indicates that they were caused by near-surface water cavitation phenomena of a sort not known to have been previously investigated. These phenomena are not directly related to cratering or to shock propagation at greater depths, but are of interest in regard to shock wave interaction in cavitated regions and water surface spall launch by strong shock waves.

Aspects of multiple-charge shock wave interaction relevant to underwater cratering are also examined briefly, and a partial explanation of the shape of the berthing basin excavated by TUGBOAT IIC is developed.

TM 71-29 March 1972

SIMULATION OF SUBSURFACE NUCLEAR EXPLOSIONS WITH CHEMICAL EXPLOSIVES

Burton, D. E. and Leahy, E. J.

A series of field experiments are being designed and theoretical studies are being conducted to select a chemical explosive and to develop explosive charge configurations and synthetic fallout material to simulate subsurface, sub-kiloton nuclear cratering explosions. The studies and experiments are directed toward determining the effects that the type and degree of stemming (full stemming, water stemming, and no stemming) have on the size of nuclear craters, the vented radioactivity, and the extent of the resulting fallout pattern. Such information for detonations in a variety of geologic media is required if nuclear explosives are to be developed as a civil and military construction tool.

The problems associated with simulating these effects through the use of chemical explosives are discussed, and partial solutions are presented. The theoretical and experimental programs will study the relative effects of the different stemming configurations in the chemical explosive case and relate the results to the nuclear case. It is suggested that these investigations will lead to optimum design criteria for simulation experiments and to a means of inferring the information which cannot be simulated.

TM 71-30 January 1972

USER'S MANUAL FOR CPM COMPUTER CODE

Wnuk, W. J.

This report is a user's manual for a computer code which calculates the event times and identifies the critical path for a Critical Path Network. This report also discusses the utilization of sorting and Julian date conversion subroutines. Input and output of the code are described in detail. However, the detailed working of the code is not discussed.

Although Appendix A presents the basic Critical Path Method concepts, this report assumes the reader is familiar with the concepts and terminology of the Critical Path Method. Appendix E lists the abbreviations utilized in this report.

TM 72-1 February 1972

USER'S MANUAL FOR MIDOL COST MINIMIZATION COMPUTER CODE

Wnuk, W. J.

This report is a user's manual for the MIDOL computer code which minimizes explosive excavation project cost for a specific single cratering-charge design which is characterized by values of depth of burial (DOB), yield (tons TNT equivalent), and media classification.

The program uses the artificial basis method to find an initial feasible solution. It then uses the simplex method of iteration to find the minimum feasible solution. The discussion of these methods are beyond the scope of this paper and the reader is referred to the references for material discussing these methods. In addition to minimizing the project cost, the program also identifies the drilling cost, the explosive cost, and the charge height to diameter ratio (L/D) which result in this minimized cost.

Input and output of the code are described in detail. FORTRAN listings and flow charts are provided in the Appendices for MIDOL, including all subroutines and subprograms. These flow charts, combined with the derivation of the project cost equation as listed in Appendix A, will provide adequate information for a detailed understanding of the working of the code.

TM 72-2 January 1972

ANTHOLOGY ON EXPLOSIVE EXCAVATION 1968-1971

Gates, R. H., Editor

This report contains fourteen of twenty-five articles prepared by members of the Corps of Engineers associated with explosive excavation during the period 1968-1971. The term "explosive excavation" is a general term which in most instances implies "cratering" or the use of large explosive charges to produce an excavation by fracturing and ejecting large volumes of soil or rock. It can also include "mounding" in which large concentrated charges are used to fracture and to loosen rock material with little or no ejection of material. Two of the articles deal exclusively with nuclear excavation. Two of the articles discuss the development of nuclear excavation for constructing an interoceanic sea-level canal. Six of the articles discuss the development and applications of chemical explosive excavation showing its use for channels, harbors, railroad cuts, and road cuts. Four articles discuss specific research areas associated with explosive excavation to include radioactivity, row-crater enhancement, and slope stability analysis. The report establishes that explosive excavation is feasible and should be considered as an alternate design procedure for many civil and military engineering projects.

TM 72-4 April 1972

USER'S MANUAL FOR MITIM TIME MINIMIZATION COMPUTER CODE

Mays, L. W.

This report is a user's manual for the MITIM computer code which minimizes explosive excavation project time for a specific charge design which is characterized by values of depth of burial (DOB), yield (tons TNT equivalent), and media classification.

The program uses the artificial basis method to find a basic (first) feasible solution. It then uses the simplex method of iteration to find the minimum feasible solution. The discussion of these methods is beyond the scope of this paper and the reader is referred to the references for material discussing these methods. In addition to minimizing the project time, the program also identifies the drilling time, the emplacement time, and the charge height to diameter ratio (L/D) which result in this minimized time.

Input and output of the code are described in detail. FORTRAN listings and flow charts are provided in the Appendices for MITIM, including all subroutines and subprograms. These flow charts, combined with the derivation of the project time equation as listed in Appendix A, will provide adequate information for a detailed understanding of the working of the code.

D. IOCS Memoranda Abstracts

(Listed sequentially by memo number)

IOCS Memo 3 November 1965

REPORT OF PETROGRAPHIC ANALYSES ON ROCK SAMPLES FROM ROUTES 17 AND 25

Captain James W. Peck and Mr. Roger A. Paul, both with the U. S. Army Engineer Nuclear Cratering Group participated in the 19-29 June 1965 I.O.C.S. Technical Planning Reconnaissance to Routes 17 and 25. During this planning reconnaissance Captain Peck and Mr. Paul performed an individual reconnaissance into the Route 25 area and separated from the main group in the Route 17 area in order to observe outcrops and collect samples. Representative specimens of the samples collected were petrographically analyzed by Dr. Jon Cummings, of California State College at Hayward under purchase order contract. The results of the sample collection activities are reported in Section II. The petrographic analyses are reported in Section III.

IOCS Memo 4 November 1965

PRELIMINARY REPORT ON THE ANALYTIC STUDY OF TIDE INDUCED CURRENTS IN A SEA-LEVEL CANAL

This study was done with a dual purpose: (1) to develop a rapid and reliable system for computing the current velocities in a sea-level canal resulting from differential entrance tides; and, (2) to predict the tidal current velocities in specific Atlantic to Pacific sea-level canal configurations.

The procedure used was to computerize the Pillsbury method for the calculation of current velocities in a sea-level canal. A brief summary of Pillsbury's development of the method is presented as well as a step by step outline of the mechanics of the solution to a current velocity problem. The complete computer program is presented in Appendix A.

The results of the initial case studies show that under the worst probable conditions velocities will not exceed 7.5 knots in any of the Panamanian alignments or 2.8 knots in the Colombian alignments. The studies further show that under mean conditions the Panama routes have a maximum velocity of 4.8 knots and in Colombia 2.1 knots. This study does not include varying the channel dimensions at constrictions to reduce the maximum velocity. The study further shows that, for Route 17A, the duration of current velocities in excess of 5 knots is 5 hr 52 min per 12-hr tidal cycle for the maximum 2% frequency. These tides occur only once a month. For the 50% frequency tide, mean conditions, the current does not reach 5 knots.

As a result of parametric studies in which the friction coefficient and the surface head were varied several conclusions are drawn.

As the friction coefficient is lowered the maximum velocity approaches some assymptotic value which appears to be not much greater than the maximums calculated in this study.

Channels are more sensitive to change in the friction coefficient in the higher range of coefficients than in the lower range.

Longer channels are less sensitive to head and friction changes than shorter channels.

In very long channels the entire head does not become effective in producing flow because of the reaction time of the channel to the surface head.

Longer channels result in reduced velocities because of increased total frictional resistance.

When substantial lengths of dredged channel, with its substantially reduced cross-section, are considered in combination with channels produced by nuclear excavation the friction coefficient of the dredged section predominates with little effect from varying the coefficient in the cratered channel.

Pending the establishment of some criteria for maximum permissible velocity or maximum acceptable duration of velocities in excess of some limit no conclusions can be drawn as to the suitability of one alignment as compared to another.

The computational system is felt to be sufficiently accurate to be used in the preliminary feasibility studies. It is also felt that with some refinement of the computer program and a reliable evaluation of the friction coefficient the program will be suitable for use in the design phase of a sea-level canal.

IOCS Memo 5 November 1965

LIST OF NOTES AND PUBLICATIONS ON SOILS AND GEOLOGIC DATA PERTAINING TO THE IOCS ENGINEERING FEASIBILITY STUDIES AVAILABLE FROM THE PERSONAL LIBRARY OF THOMAS F. THOMPSON, CONSULTING ENGINEERING GEOLOGIST

On 8 November 1965, NCG personnel cataloged an extensive collection of soils and geologic data on the Panama Canal Zone, the Darien Region of Panama, and the Atrato-Truando Region of Colombia, all belonging to Mr. Thomas F. Thompson, Consulting Engineering Geologist. This list is shown in Section III. At that time, Mr. Thompson indicated that he would be happy to furnish this information, on a loan basis, to all parties interested in the engineering feasibility studies.

Inquiries concerning Mr. Thompson's collection of information should be addressed to:

Mr. Thomas F. Thompson
Consulting Engineering Geologist
866 Burlway Road
Burlingame, California

Telephone: Area Code 415, 342-4731

IOCS Memo 6 December 1965

PRELIMINARY ALIGNMENT INVESTIGATION: ROUTE 17

Route 17 is the designation given to an area in the Darien Region of Panama that is considered as a construction site for an interoceanic sea-level canal. Letters will be added to this area designation to indicate particular alignments to be considered.

This study investigates possible alignments for Route 17 and after consideration of limiting factors, selects the most favorable alignments for further consideration.

The analysis revealed that the zone within which the ultimate alignment apparently will lie is limited in width by the following factors:

a. There is only one pass across the Divide on the Atlantic end which appears feasible for nuclear excavation in terms of maximum elevation, width, and straightness. This is Sasardi Pass through which the routes named 17A and 17B pass. Even though the Surcurti Pass and Carreto Pass are at the lowest elevations, the narrowness of those passes and the number of turns required in the channel preclude further consideration.

b. The Pacific terminus of the alignment must lie within San Miguel Bay to hold the canal length to a minimum and to take advantage of this large natural harbor.

c. The lower Chucunaque valley appears to be unsatisfactory for nuclear excavation because of vast swamp areas and deep soils.

d. A shift of the alignment to the north of Routes 17A or 17B after crossing the Divide causes a significant increase in length without providing any important advantages in topography, geology, and hydrology.

The following sections of this study relate the information and data used in the analysis and the criteria presently applied in evaluating potential alignments.

Within the zone defined by the foregoing limitations, Route 17A appears to be most favorable from the standpoint of preliminary slope stability, hydrological and channel hydraulic considerations. However, the limited data available do not permit a positive conclusion as to which is the best alignment. With the data available, it appears that the final alignment will lie in a band which includes the alignments presently being considered.

IOCS MEMO 7 December 1965

PRELIMINARY ALIGNMENT INVESTIGATION: ROUTE 25

Route 25 is the designation given to an area in northwest Colombia considered as a construction site for an interoceanic sea-level canal. Letters will be added to this area designation to indicate particular alignments to be considered.

This study investigates possible alignments for Route 25, and after consideration of limiting factors, selects two alignments for further consideration. Route 25A would be excavated by conventional means for the first 320,000 ft and Route 25B could be

excavated by nuclear means for the entire length of the route. These alignments present the options in excavation and appear to represent the extremes of possible orientation because of the following considerations:

a. The divide can only be crossed at one location. This can be observed on Inclosure C, Divide Profile.

b. The alignment cannot be shifted to the west because of a relatively high mountain range that exceeds the limiting elevation for the largest device (10 Mt).

c. It is not desirable to shift the alignment eastward because of the swamp area that would be encountered and because of flood control problems associated with the Atrato River. A shift in this direction would also lengthen the alignment.

The following sections of this study relate the information and data used in the analysis and the criteria presently applied in evaluating potential alignments.

The final section of this investigation discusses and compares the two alignments, 25A and 25B, with regard to the criteria applied. The limited data available does not permit a positive conclusion as to which is the better alignment. Route 25B does appear more favorable from engineering aspects but these advantages may be outweighed by safety and political problems associated with nuclear excavation in the northern section of the route. Within the zone of investigation, there will be an optimum alignment which can be selected after the data are collected on the site and the data evaluation and engineering studies are complete.

IOCS Memo 8 March 1966

PRELIMINARY ALIGNMENT INVESTIGATION: ROUTE 17

Route 17 is the designation given to an area in the Darien Region of Panama that is considered as a potential site for an interoceanic sea-level canal. Letters will be added to this area designation to indicate particular alignments to be considered.

This study investigates possible alignments for Route 17 and after consideration of limiting factors, selects the most favorable alignments for further consideration.

The analysis revealed that the zone within which the ultimate alignment apparently will lie is limited in width by the following factors:

a. There is only one pass across the Divide on the Atlantic end which appears feasible for nuclear excavation in terms of maximum elevation, width, and straightness. This is Sasardi Pass through which the routes named 17A and 17B pass. Even though the Surcurti Pass and Carreto Pass are at the lowest elevations, the narrowness of those passes and the number of turns required in the channel preclude further consideration.

b. The Pacifi terminus of the alignment must lie within San Miguel Bay to hold the canal length to a minimum and to take advantage of this large natural harbor.

c. The lower Chucunaque valley appears to be unsatisfactory for nuclear excavation because of vast swamp areas and deep soils.

d. A shift of the alignment to the north of Routes 17A or 17B after crossing the Divide causes a significant increase in length without providing any important advantages in topography, geology, and hydrology.

The following sections of this study relate the information and data used in the analysis and the criteria presently applied in evaluating potential alignments.

Within the zone defined by the foregoing limitations, Route 17A appears to be most favorable from the standpoint of preliminary slope stability, hydrological and channel hydraulic considerations. However, the limited data available do not permit a positive conclusion as to which is the best alignment. With the data available, it appears that the final alignment will lie in a band which includes the alignments presently being considered.

IOCS Memo 9 March 1966

PRELIMINARY ALIGNMENT INVESTIGATION: ROUTE 25

Route 25 is the designation given to an area in northwest Colombia considered as a potential site for an interoceanic sea-level canal. Letters will be added to this area designation to indicate particular alignments to be considered.

This study investigates possible alignments for Route 25, and after consideration of limiting factors, selects two alignments for further consideration. Route 25A would be excavated by conventional means for the first 320,000 ft and Route 25B could be excavated by nuclear means for the entire length of the route. These alignments present the options in excavation and appear to represent the extremes of possible orientation because of the following considerations:

a. The divide can only be crossed at one location. This can be observed on Inclosure C, Divide Profile.

b. The alignment cannot be shifted to the west because of a relatively high mountain range that exceeds the limiting elevation for the largest device (10 Mt).

c. It is not desirable to shift the alignment eastward because of the swamp area that would be encountered and because of flood control problems associated with the Atrato River. A shift in this direction would also lengthen the alignment.

The following sections of this study relate the information and data used in the analysis and the criteria presently applied in evaluating potential alignments.

The final section of this investigation discusses and compares the two alignments, 25A and 25B, with regard to the criteria applied. The limited data available does not permit a positive conclusion as to which is the better alignment. Route 25B does appear more favorable from engineering aspects but these advantages may be outweighed by safety and political problems associated with nuclear excavation in the northern section of the route. Within the zone of investigation, there will be an optimum alignment which can be selected after the data are collected on the site and the data evaluation and engineering studies are complete.

IOCS Memo 10 April 1966

SECOND REPORT OF PETROGRAPHIC ANALYSES OF ROCK SAMPLES FROM ROUTES 17 AND 25

The U.S. Army Engineer Nuclear Cratering Group (NCG) has obtained petrographic analyses of rock samples collected along the proposed sea level canal routes. These analyses were performed, under purchase order contract to NCG, by Dr. Jon C. Cummings of California State College at Hayward. The results of seven of these analyses are reported in this memorandum. Two samples, 29-5-2 and T-4 collected near the Pacific terminus of Route 17, were identified as Diatomaceous Dolomite and Water Laid Tuff respectively. Sample 20-2, taken from the continental divide region of Route 25, was identified as Spilitic Diabase. Four samples were taken from the Atrato Basin region of Route 25 near Sautata and were identified as: 28-1, Water Laid Lithic Tuff; IH-1.1, Calcareous Foraminiferal Mudstone; IH-2.1, Volcanic Graywacke Conglomerate; and IH-2.2, Tuffaceous Mudstone.

IOCS Memo 11 May 1966

GEOMORPHIC ANALYSIS OF ROUTE 17

Route 17 of the proposed interoceanic sea-level canal have been broken into twenty-five areas by geomorphic analysis. Within each of these areas the drainage network, the depths of channels, and the maximum natural slopes are similar.

Although the dominant structural trend is parallel to the Isthmus of Panama, several distinct lineations normal to this direction can be traced nearly across the isthmus.

In Sasardi Gap, where Route 17 crosses the continental divide, the geomorphic evidence favors an interpretation of dipping layered rocks. There does not appear to be a massive crystalline core exposed at the range crest at this locality.

The region adjacent to San Miguel Bay is broken by many faults or fracture systems, each of which is referred to one of five directions. The ranges in this region are apparently composed of dipping layered rocks, except on Punta Sabana, where a distinctive physiography marks the outcrop of basalt.

IOCS Memo 12 June 1966

PRELIMINARY ALIGNMENT INVESTIGATION: ROUTE 17

Route 17 is the designation given to an area in the Darien Region of Panama that is considered as a potential site for an interoceanic sea-level canal. Letters have been added to this area designation to indicate particular alignments to be considered.

This study investigates possible alignments for Route 17 and after consideration of limiting factors, selects the most favorable alignments for further consideration.

The analysis revealed that the zone within which the ultimate alignment apparently will lie is limited in width by the following factors:

a. There is only one pass across the Divide on the Atlantic end which appears feasible for nuclear excavation in terms of maximum elevation, width, and straightness. This is Sasardi Pass through which the routes named 17A and 17B pass. Even though the Surcurti Pass and Carreto Pass are at the lowest elevations, the narrowness of those passes and the number of turns required in the channel preclude further consideration.

b. The Pacific terminus of the alignment must lie within San Miguel Bay to hold the canal length to a minimum and to take advantage of this large natural harbor.

c. The lower Chucunaque valley appears to be unsatisfactory for nuclear excavation because of vast swamp areas and deep soils.

d. A shift of the alignment to the north of Routes 17A or 17B after crossing the Divide causes a significant increase in length without providing any important advantages in topography, geology, and hydrology.

The following sections of this study relate the information and data used in the analysis and the criteria presently applied in evaluating potential alignments.

Within the zone defined by the foregoing limitations, Route 17A appears to be most favorable from the standpoint of preliminary slope stability, hydrological and channel hydraulic considerations. However, the limited data available do not permit a positive conclusion as to which is the best alignment. With the data available, it appears that the optimum alignment will lie in a band which includes the alignments presently being considered.

IOCS Memo 13 June 1966

NUCLEAR EXCAVATION DESIGN (PRELIMINARY): ROUTE 25

Route 25 is the designation given to an area in northwest Colombia considered as a potential site for an interoceanic sea-level canal. Letters will be added to this area designation to indicate particular alignments to be considered.

This study investigates possible alignments for Route 25, and after consideration of limiting factors, selects two alignments for further consideration. Route 25A would be excavated by conventional means for the first 320,000 ft and Route 25B could be excavated by nuclear means for the entire length of the route. These alignments present the options in excavation and appear to represent the extremes of possible orientation because of the following considerations:

a. The divide can only be crossed at one location. This can be observed on Inclosure C, Divide Profile.

b. The alignment cannot be shifted to the west because of a relatively high mountain range that exceeds the limiting elevation for the largest device (10 Mt).

c. It is not desirable to shift the alignment eastward because of the swamp area that would be encountered and because of flood control problems associated with the Atrato River. A shift in this direction would also lengthen the alignment.

The following sections of this study relate the information and data used in the analysis and the criteria presently applied in evaluating potential alignments.

The final section of this investigation discusses and compares the two alignments, 25A and 25B, with regard to the criteria applied. The limited data available does not permit a positive conclusion as to which is the better alignment. Route 25B does appear more favorable from engineering aspects but these advantages may be outweighed by safety and political problems associated with nuclear excavation in the northern section of the route. Within the zone of investigation, there will be an optimum alignment which can be selected after the data are collected on the site and the data evaluation and engineering studies are complete.

IOCS Memo 14 July 1966
GEOMORPHIC ANALYSIS OF ROUTE 25

Route 25, one of the locations proposed for an interoceanic sea-level canal, has been divided into 22 zones, each having distinctive physiographic properties. Within each of these areas the drainage network, the depths of channels, and the maximum natural slopes are similar.

The general shapes and distribution of the geomorphic zones agree roughly with the geologic maps presently used in the canal studies. However, an extensive area in the eastern Sierra los Saltos, previously mapped as soft to moderately hard Tertiary sedimentary rocks, displays physiographic characteristics that suggest an exceptionally competent rock type.

At the northeastern terminus a range that separates the valley of Rio Tanela from the Gulf of Uraba has the strongly linear topography typical of a terrane of steeply dipping layered rocks.

Distinct lineations that probably mark faults occur near the edge of Serrania del Darien in the northeastern part of the study area and near the Rio Truando in and at the border of Sierra los Saltos.

IOCS Memo 15 September 1966
NUCLEAR EXCAVATION DESIGN (PRELIMINARY): ROUTE 17

Route 17 is the designation given to an area in the Darien Region of Panama that is considered as a potential site for an interoceanic sea-level canal. Letters have been added to this area designation to indicate particular alignments to be considered.

This study investigates possible alignments for Route 17 and after consideration of limiting factors, selects the most favorable alignments for further consideration.

The analysis revealed that the zone within which the ultimate alignment apparently will lie is limited in width by the following factors:

a. There is only one pass across the Divide on the Atlantic end which appears feasible for nuclear excavation in terms of maximum elevation, width, and straightness. This is Sasardi Pass through which all the proposed alignments pass. Even though the Surcurti Pass and Carreto Pass are at the lowest elevations, the narrowness of those passes and the number of turns required in the channel preclude further consideration.

b. The Pacific terminus of the alignment must lie within San Miguel Bay to hold the canal length to a minimum and to take advantage of this large natural harbor.

c. The lower Chucunaque valley appears to be unsatisfactory for nuclear excavation because of vast swamp areas and deep soils.

d. A shift of the alignment to the north of Routes 17A or 17B after crossing the Divide causes a significant increase in length without providing any important advantages in topography, geology, and hydrology.

The following sections of this study relate the information and data used in the analysis and the criteria presently applied in evaluating potential alignments.

Within the zone defined by the foregoing limitations, Route 17A appears to be most favorable from the standpoint of preliminary slope stability, hydrological and channel hydraulic considerations. However, the limited data available does not permit a positive conclusion as to which is the best alignment. With the data available, it appears that the optimum alignment will lie in a band which includes the alignments presently being considered.

IOCS Memo 16 September 1966

NUCLEAR EXCAVATION DESIGN (PRELIMINARY): ROUTE 25

Route 25 is the designation given to an area in northwest Colombia considered as a potential site for an interoceanic sea-level canal. Letters will be added to this area designation to indicate particular alignments to be considered.

This study investigates possible alignments for Route 25, and after consideration of limiting factors, selects two alignments for further consideration. Route 25A would be excavated by conventional means for the first 320,000 ft and Route 25B could be excavated by nuclear means for the entire length of the route. These alignments present the options in excavation and appear to represent the extremes of possible orientation because of the following considerations:

a. The divide can only be crossed at one location. This can be observed on Inclosure C, Divide Profile.

b. The alignment cannot be shifted to the west because of a relatively high mountain range that exceeds the limiting elevation for the largest device (10 Mt).

c. It is not desirable to shift the alignment eastward because of the swamp area that would be encountered and because of flood control problems associated with the Atrato River. A shift in this direction would also lengthen the alignment.

The following sections of this study relate the information and data used in the analysis and the criteria presently applied in evaluating potential alignments.

The final section of this investigation discusses and compares the two alignments, 25A and 25B, with regard to the criteria applied. The limited data available does not permit a positive conclusion as to which is the better alignment. Route 25B does appear more favorable from engineering aspects but these advantages may be outweighed by safety and political problems associated with nuclear excavation in the northern section of the route. Within the zone of investigation, there will be an optimum alignment which can be selected after the data are collected on the site and the data evaluation and engineering studies are complete.

IOCS Memo 17 December 1966

SPECIAL REPORT 1966: CONSTRUCTION OF AN ISTHMIAN SEA-LEVEL CANAL BY NUCLEAR METHODS: ROUTE 8, NICARAGUA-COSTA RICA

This study investigates the cost, safety and other factors involved in the construction of a sea-level canal by nuclear excavation in the general area of the Nicaragua-Costa Rica border. This area has been designated Route 8. The criteria used in development of this study are the same as those used in the 1964 Isthmian Canal Studies except where advances in technology require updating.

IOCS Memo 18 December 1966

NUCLEAR EXCAVATION DESIGN (PRELIMINARY): ROUTE 17

Route 17 is the designation given to an area in the Darien Region of Panama that is considered as a potential site for an interoceanic sea-level canal. Letters have been added to this area designation to indicate particular alignments to be considered.

This study investigates possible alignments for Route 17 and after consideration of limiting factors, selects the most favorable alignments for further consideration.

The analysis revealed that the zone within which the ultimate alignment apparently will lie is limited in width by the following factors:

a. There is only one pass across the Divide on the Atlantic end which appears feasible for nuclear excavation in terms of maximum elevation, width, and straightness. This is Sasardi Pass through which all the proposed alignments pass. Even though the Surcurti Pass and Carreto Pass are at the lowest elevations, the narrowness of those passes and the number of turns required in the channel preclude further consideration.

b. The Pacific terminus of the alignment must lie within San Miguel Bay to hold the canal length to a minimum and to take advantage of this large natural harbor.

c. The lower Chucunaque valley appears to be unsatisfactory for nuclear excavation because of vast swamp areas and deep soils.

d. A shift of the alignment to the north of Routes 17A or 17B after crossing the Divide causes a significant increase in length without providing any important advantages in topography, geology, and hydrology.

The following sections of this study relate the information and data used in the analysis and the criteria presently applied in evaluating potential alignments.

Within the zone defined by the foregoing limitations, Route 17A appears to be most favorable from the standpoint of preliminary slope stability, hydrological and channel hydraulic considerations. However, the limited data available do not permit a positive conclusion as to which is the best alignment. With the data available, it appears that the optimum alignment will lie in a band which includes the alignments presently being considered.

IOCS Memo 19 December 1966

NUCLEAR EXCAVATION DESIGN (PRELIMINARY): ROUTE 25

Route 25 is the designation given to an area in northwest Colombia considered as a potential site for an interoceanic sea-level canal. Letters will be added to this area designation to indicate particular alignments to be considered.

This study investigates possible alignments for Route 25, and after consideration of limiting factors, selects two alignments for further consideration. Route 25A would be excavated by conventional means for the first 320,000 ft and Route 25B could be excavated by nuclear means for the entire length of the route. These alignments present the options in excavation and appear to represent the extremes of possible orientation because of the following considerations:

a. The divide can only be crossed at one location. This can be observed on Inclosure C, Divide Profile.

b. The alignment cannot be shifted to the west because of a relatively high mountain range that exceeds the limiting elevation for the largest device (10 Mt).

c. It is not desirable to shift the alignment eastward because of the swamp area that would be encountered and because of flood control problems associated with the Atrato River. A shift in this direction would also lengthen the alignment.

The following sections of this study relate the information and data used in the analysis and the criteria presently applied in evaluating potential alignments.

The final section of this investigation discusses and compares the two alignments, 25A and 25B, with regard to the criteria applied. The limited data available do not permit a positive conclusion as to which is the better alignment. Within the zone of

investigation, there will be an optimum alignment which can be selected after the data are collected on the site and the data evaluation and engineering studies are complete.

IOCS Memo 20 March 1967

SPECIAL REPORT 1966: CONSTRUCTION OF AN ISTHMIAN SEA-LEVEL CANAL BY NUCLEAR METHODS: ROUTE 8, NICARAGUA-COSTA RICA (Revised)

This study investigates the cost, safety and other factors involved in the construction of a sea-level canal by nuclear excavation in the general area of the Nicaragua-Costa Rica border. This area has been designated Route 8. The criteria used in development of this study are the same as those used in the Isthmian Canal Studies—1964 except where advances in technology require updating.

IOCS Memo 21 March 1967

NUCLEAR EXCAVATION DESIGN (PRELIMINARY): ROUTE 17

This memorandum presents the current status of the study on nuclear excavation design of a sea-level canal across the Isthmus of Panama in the area designated Route 17.

IOCS Memo 22 March 1967

NUCLEAR EXCAVATION DESIGN (PRELIMINARY): ROUTE 25

This memorandum presents the current status of the study on nuclear excavation design of a sea-level canal across the Isthmus of Panama in the area designated Route 25.

IOCS Memo 23 March 1967

SUMMARY REPORT: CONSTRUCTION OF AN ISTHMIAN SEA-LEVEL CANAL BY NUCLEAR METHODS: ROUTE 8, NICARAGUA-COSTA RICA

This report summarizes the findings and recommendations of IOCS Memorandum NCG-20, entitled "Special Report—1966, Construction of an Isthmian Sea-Level Canal by Nuclear Methods, Route 8, Nicaragua-Costa Rica (Revised), 15 March 1967.

In 1959, the Panama Canal Company and the Atomic Energy Commission joined in a study of using nuclear methods to excavate an Isthmian sea-level canal. Five general routes were considered: one in Mexico, one in Nicaragua and Costa Rica, two in Panama, and one in Colombia. The conclusions of that study, reported in Isthmian

Canal Plans—1960, were that nuclear excavation was feasible and could be done safely at a remote site for substantially less cost than for converting the present Panama Canal to sea-level by conventional means.

By 1964, advances in the nuclear excavation technology warranted a reevaluation of the feasibility of constructing a sea-level canal by nuclear methods. Consequently, the Panama Canal Company, the Atomic Energy Commission and the Corps of Engineers made a much more comprehensive study of nuclear excavation of a sea-level canal project as part of Isthmian Canal Studies—1964. Annex III of that report evaluated the two alternative routes considered most feasible from a technical standpoint: the Sasardi-Morti Route, also known as Route 17, and the Atrato-Truando Route, called Route 25. The 1964 Studies concluded that nuclear excavation along either route was technically feasible and safe.

Public Law 88-609, enacted in September 1964, authorized the appointment of a Commission to make a full and complete investigation, including necessary on-site surveys, to determine the best means of construction and the most favorable site for an Isthmian sea-level canal. As a consequence, there is renewed interest in examining all possible routes so that the best solution can be obtained. This report summarizes the results of a recent reevaluation of the feasibility of constructing a sea-level canal by nuclear excavation methods in the Nicaragua-Costa Rica border area along an alignment designated as Route 8A.

Selected features of alignment 8A are compared with the same features of Routes 17 and 25 developed in the 1964 Studies. It is important to note that Route 8A would require approximately four times as many detonations as Route 17 as designed in the 1964 Studies. This study of Route 8 assumes that two detonations per month would be feasible under existing meteorological patterns, resulting in a 48-month period of emplacement drilling and detonations. The current detonation schedules for Routes 17 and 25 assume one detonation per month. Should this frequency of detonations prove applicable to Route 8A, 77 months would be required to complete the detonations.

Clearly, the most significant characteristic of Route 8A is the population density and state of economic development of the Nicaragua-Costa Rica regions within the influence of significant levels of explosion effects. When contrasted with the remote sites of Routes 17 and 25, the disadvantages of Route 8A are obvious. Based upon the effects estimates in this study, nuclear excavation of a sea-level canal in the Route 8 area would cause serious disruption of the national economies of Nicaragua and Costa Rica. Applying the criteria for evacuation used in Isthmian Canal Studies—1964, an estimated 1,170,000 residents of Nicaragua and Costa Rica would require evacuation and resettlement for a period ranging between four and six and one-half years. In addition, approximately 175,000 people residing within the range of potentially damaging air blast overpressures would require temporary evacuation during detonation periods. This temporary and semipermanent evacuation would involve more than 75% of the population of Costa Rica and more than 50% of its land area. Because such massive evacuation is not considered reasonable or practical, no attempt was made to develop cost estimates

for evacuation and compensation for damages. A preliminary cost estimate, exclusive of nuclear operations and public safety costs, has been developed for Route 8A. This estimate is compared with the total cost estimates for Routes 17 and 25 developed in the 1964 Studies.

IOCS Memo 24 June 1967
NUCLEAR EXCAVATION DESIGN (PRELIMINARY): ROUTE 17

This memorandum presents the current status of the study on nuclear excavation design of a sea-level canal across the Isthmus of Panama in the area designated Route 17.

In the Plan for Study of Engineering Feasibility of Alternate Sea-Level Canal Routes Connecting the Atlantic and Pacific Oceans, the U.S. Army Engineer Nuclear Cratering Group is assigned the responsibility for performing the nuclear excavation design of the sea-level channels for Routes 17 and 25.

Previous memoranda in this series identified the zone within which the ultimate alignment will lie, defined the primary area of site investigations, and analyzed the engineering features of three alternative alignments. The following factors were considered in their selection:

1. There is only one pass across the Divide on the Atlantic end which appears feasible for nuclear excavation in terms of maximum elevation, width, and straightness. This is Sasardi Pass through which all the proposed alignments pass. Even though the Surcurti Pass and Carreto Pass are at the lowest elevations, the narrowness of these passes and the number of turns required in the channel precluded their further consideration.

2. The Pacific terminus of the alignment must lie within San Miguel Bay to hold the canal length to a minimum and to take advantage of this large natural harbor.

3. The lower Chucunaque Valley appears to be unsatisfactory for nuclear excavation because of vast swamp areas and deep soils.

4. A shift of the alignment to the north of Routes 17A or 17B after crossing the Divide causes a significant increase in length without providing any apparent advantages in topography, geology, and hydrology.

ICOS Memo 25 December 1967
NUCLEAR EXCAVATION DESIGN (PRELIMINARY): ROUTE 17

This memorandum presents the current status of the study on nuclear excavation design of a sea-level canal across the Isthmus of Panama in the area designated Route 17.

IOCS Memo 26 December 1967

NUCLEAR EXCAVATION DESIGN (PRELIMINARY): ROUTE 25

This memorandum presents the current status of the study on nuclear excavation design of a sea-level canal across the Isthmus of Panama in the area designated Route 25.

IOCS Memo 27 May 1968

ANALYSIS OF ARRAY CONCEPTS FOR NUCLEAR EXCAVATION OF THE CHUCUNAQUE VALLEY SHALES, ROUTE 17A (Final Report)

This report presents a comprehensive analysis of the feasibility and impact of incorporation of a two-pass, triple row array detonation system into the nuclear excavation design of a sea-level canal through the Chucunaque Valley clay shale reach of Route 17A in Panama.

This report supersedes NCG-27, dated 22 January 1968.

The results of the I.O.C.S. subsurface geology data collection program for Route 17 have indicated that approximately 20 mi of that route alignment passes through the Chucunaque Valley clay shale formation. Laboratory testing of samples of this material have revealed that the Chucunaque clay shales are characterized by high natural moisture contents, high liquid limits, high montmorillonite content and low residual friction angles (7-9 deg). These characteristics are typical of clay shale materials which are "troublesome" from a long-term slope stability standpoint. Current understanding of the "progressive failure" of slopes formed in clay shale similar to that occurring in Chucunaque Valley indicates that the long-term "safe" angle of inclination of the slope may approach the characteristic residual friction angle. It has been deemed appropriate, therefore, to initiate a joint Atomic Energy Commission/Corps of Engineers research effort to: (1) develop a more comprehensive understanding of the long-term stability of saturated, weak materials, such as the Route 17 Chucunaque Valley clay shales; and (2) develop techniques for using nuclear explosives to produce linear craters with flat slopes in saturated, weak materials.

IOCS Memo 28 August 1969

ELEMENTS OF EMPLACEMENT CONSTRUCTION DESIGN FOR AN ISTHMIAN SEA-LEVEL CANAL

This report provides information on the current large diameter hole drilling technology as it pertains to emplacement construction for nuclear excavation of an Isthmian sea-level canal. It describes the applicable drilling techniques and equipment. Hole casing requirements and stemming procedures are outlined. The elements of an emplacement drilling program are discussed, and cost estimating and scheduling criteria

are developed. The information in this report is pertinent to the design of emplacement construction programs for Routes 8, 17, and 25.

The first deeply buried nuclear explosion in the U.S. was Project Rainier, which was conducted in 1957 in a tunnel under Rainier Mesa at the Nevada Test Site of the Atomic Energy Commission. Since the Rainier event, hundreds of nuclear explosions have been performed in tunnels and in large diameter drill holes.

The Fort Worth District of the U.S. Army Corps of Engineers recently completed a study of emplacement construction technology sponsored by the U.S. Army Engineer Nuclear Cratering Group. This study revealed that large diameter drilling is the most appropriate method of emplacement construction for an Isthmian sea-level canal.

IOCS Memo 29 September 1969
TOPOGRAPHIC ANALYSIS OF ROUTE 25

This memorandum develops the topographic base used in the feasibility study of construction of a transisthmian sea-level canal in the Route 25 area of northwestern Colombia. Topographic data are required for estimates of conventional channel excavation quantities, preliminary design of flood control and river diversion facilities, development of access road networks, and determination of the nuclear explosive yield requirements.

Prior to the data collection efforts made in the field in 1967 the best available source of topographic data for the Route 25 area was a special series of 1:50,000-scale maps produced in 1964 by the Army Map Service (AMS) and the Inter-American Geoditic Survey (IAGS). These maps were produced photogrammetrically from aerial photographs taken in 1962.

Field surveys were performed by the Office of Interoceanic Canal Studies (OICS) in 1967 and 1968 to check the reliability of the topographic data for the current studies. The results of those surveys are reported in IOCS Memorandum FD-76 dated June 1968.

IOCS Memo 30 September 1969
TOPOGRAPHIC ANALYSIS OF ROUTE 17

This memorandum develops the topographic base required for the feasibility study of constructing a transisthmian sea-level canal in the Route 17 area of eastern Panama. Topographic data are required for estimates of conventional channel excavation quantities, preliminary design of flood control and river diversion facilities, development of access road networks, and determination of the nuclear explosive yield requirements.

When the current canal studies were initiated, the best available source of topographic data for Route 17 was a special series of maps produced in 1964 by the Army

Map Service (AMS) in conjunction with the Inter-American Geodetic Survey (IAGS). These maps were produced at a scale of 1:50,000 by photogrammetric methods from aerial photographs taken in 1962.

The AMS maps were subject to considerable error for a number of reasons. The aerial photography was performed with wide angle lens cameras, which resulted in some distortion in the photographs. A dense jungle canopy, as high as 200 ft, obscured the ground. In addition, the survey ground control for the maps was of unknown accuracy. In view of these factors, field surveys were performed by the Office of Interoceanic Canal Studies in 1966 and 1967 to obtain more reliable topographic data for the current studies. The results of the topographic surveys are reported in Interoceanic Canal Studies (IOCS) Memorandum FD-33, dated July 1967.

IOCS Memo 31 September 1969

SUMMARY OF GEOLOGY AND ROCK PHYSICAL PROPERTIES: ROUTE 17

The purpose of this report is to summarize in one volume the geology of Route 17 and the physical properties of its rocks, as they pertain to nuclear excavation design. A geologic map and cross-sections are presented, and the rock units shown thereon and their geological structure are discussed briefly. Results of physical properties investigations are presented, primarily in graphic form.

IOCS Memo 32 April 1970

SLAKING BEHAVIOR OF THE CHOCO VOLCANICS

This report provides the results of slaking tests performed on samples of the Choco Volcanics, northwestern Colombia, and evaluates these data in terms of the potential weathering characteristics of the volcanic rocks.

IOCS Memo 33 October 1969

SUMMARY OF GEOLOGY AND ROCK PHYSICAL PROPERTIES: ROUTE 25

The purpose of this report is to summarize in one volume the geology of Route 25 and the physical properties of its rocks, as they pertain to nuclear excavation design. Because nuclear excavation is applicable only in the southwestern, or Pacific, portion of the route, the Atlantic portion is discussed only briefly. For the Pacific portion, a geologic map, a geologic profile along Route 25E, and three geologic sections are given. The rock units and structural geology are discussed. Pertinent physical-properties test results and down-hole geophysical data are shown graphically.

In the period 1966-1969, to gather certain specific information required for design of a sea-level canal, a detailed geologic data-collection program was carried out along Route 25. The operations performed and their interrelationships are summarized.

These activities were carried out under the supervision of the Field Director, Office of Interoceanic Canal Studies. Results were published from time to time in a series of data-collection reports, designated IOCS FD Memoranda. Those memoranda dealing with geology have been used as the basis for this report. Chief reliance has been placed on FD-80, Geology Final Report, Route 25 (Volume I, October 1968, and Volume II, April 1969). References to specific FD Memoranda are made in places in this report, and a bibliography is included at the end.

IOCS Memo 34 October 1970

SLOPE STABILITY IN THE CHOCO VOLCANICS

This report presents a study of the effects of rock strength and slaking behavior on stability of high rock slopes along Route 25.

Route 25 is a proposed sea-level canal route through northwestern Colombia. Twenty miles of the alignment are being considered for nuclear excavation; 15 mi of this portion lies on volcanic rocks of the Choco and Saltos highlands called Choco volcanics. The Choco volcanics are principally autobreccias, tuffs, pillow basalts and lava flows of oceanic basalt, the latter having been extruded onto the sea floor and altered in place. Alteration products include montmorillonite and several zeolite materials.

The altered basalts have lower unconfined compressive strength and density, and higher water content, than fresh basalts. The rock core sample behavior in the laboratory has been used to classify the rock as "intermediate quality."

IOCS Memo 35 December 1970

ENGINEERING PROPERTIES OF CRATERS AND PRINCIPLES OF CRATER STABILITY

The report describes the engineering characteristics of nuclear craters and reviews the state-of-the-art for assessing the long-term stability of nuclear crater slopes. Crater zones are delineated and their properties described. Emphasis is placed on compressibility, permeability, and shear strength of the cratered materials. A portion of the report is devoted to a discussion of the factors affecting slope stability in clay shale and rock and modes of failure. It is concluded that failure surfaces in rock would follow existing planes of weakness and that clay shales have rock-like characteristics over the short term and clay-like characteristics over the long term. Because the current technology does not permit the precise measurements of material

properties required for the analytical approach, the empirical approach is the most appropriate method for evaluating the potential stability of the proposed nuclear sea-level canal.

IOCS Memo 36 August 1970

LIQUEFACTION POTENTIAL OF ATRATO VALLEY SOILS: ROUTE 25

The possible liquefaction of the soils in the Atrato Lowlands from seismic activity induced by nuclear explosive excavation of a portion of Route 25 is reviewed and evaluated. Silty sands from borings along Route 25 are noted to have characteristics similar to soils with known liquefaction potential. Estimates of expected seismic activity are evaluated both analytically and empirically. On the basis of the arguments presented, liquefaction of soils in the Atrato Lowlands seems highly unlikely.

E. PNE Report Abstracts

(Listed sequentially by report number)

PNE 234F March 1964

STABILITY OF CRATER SLOPES

Strohm, W. E., Ferguson, J. S., and Krinitzsky, E. L.

This report presents the results of preshot and postshot field and laboratory investigations of the foundation soils in the vicinity of the SEDAN shot. The preshot investigations included a review of all available information on geologic and soil conditions in the area. Published literature pertaining to general geology, soils, and groundwater and geophysical data on the general area were examined to obtain guidance in the interpretation of data and observations. Preshot fieldwork consisted of field mapping of exposed geologic units, borings in the vicinity of the proposed shot, geophysical logging of the drill holes, and laboratory tests to evaluate the existing engineering properties of the soils. Postshot investigations consisted of trench excavations and crater walls, field borings, geophysical logging of the drill holes, and laboratory testing of representative samples. The mechanics of crater development are deduced from the results of the field investigations. Comparisons of field and laboratory measurements are made to demonstrate changes in engineering properties resulting from the blast. The effects of the altered properties of the foundation materials on their adequacy with respect to supporting engineering structures and in regard to the immediate and long-term stability of the crater slopes are discussed. Recommendations concerning measurements to be made at similar future events are presented.

PNE 300P May 1963

SCOPE OF CHEMICAL EXPLOSIVE CRATERING EXPERIMENTS

Graves, E., Jr., Wray, W. R., and Pierce, R. B.

This report provides a general description of the Pre-BUGGY chemical explosive experiments. These experiments consisted of a series of single- and multiple-charge detonations designed to refine our knowledge of channel size as a function of charge spacing, and to obtain data on venting of explosion products from a row of spherical charges detonated in alluvium.

A basic series of six single-charge detonations and four multiple-charge detonations of five charges in a row was executed in Area 5 of the Nevada Test Site from November 1962 through February 1963. Each charge contained 1,000 lb of nitromethane with a La^{140} tracer.

Preliminary examination of the results indicates that:

(1) When charges were spaced at 1.0 single-charge crater radius, the channel depth and width were larger than the diameter and depth of a single-charge crater.

(2) Small increases in spacing resulted in considerable reduction of channel depth and a smaller reduction in width.

(3) The channel shape at spacings of 1.5 single-charge crater radii was very uneven.

(4) When the ratio of the depth-of-burst to depth-of-crater was about two, the venting of explosion products from a row-charge detonation was less than from single-charge detonations.

PNE 301F August 1964

VENTING MEASUREMENTS—PROJECT PRE-BUGGY

Wray, W. R. and Pierce, R. B.

The purpose of the venting measurements program of the Pre-BUGGY chemical explosives experiment was to compare the amount of a radioactive tracer that escaped and was deposited with the local fallout (vented fraction) from single-charge and multiple-charge detonations.

A basic series of six single-charge detonations and four multiple-charge detonations of five charges in a row was executed in Area 5 of the Nevada Test Site from November 1962 through February 1963. Each charge contained 1000 lb of nitromethane with a La^{140} tracer.

The experiment consisted of placing known quantities of La^{140} in the explosive charge, detonating the charge, measuring the distribution of the La^{140} by sampling techniques (2 ft by 2 ft trays), plotting fallout patterns, integrating the patterns, and determining the vented fraction.

The vented fraction of the four row detonations was less than the vented fraction from each of the two single-charge detonations with the same depth of burst as the rows. The final conclusion was that the vented fraction from a multiple-device nuclear detonation would be less than the vented fraction from a single-device nuclear detonation with the same scaled depth of burst.

PNE 302 February 1965

EMPLACEMENT AND FIRING OF HIGH-EXPLOSIVE CHARGES AND CRATER MEASUREMENTS—PROJECT PRE-BUGGY

Rooke, A. D., Jr. and Davis, L. K.

Six 1,000-lb high-explosive (HE) charges, each containing a capsule of radioactive tracer (lanthanum 140), were detonated at depths varying from 15.0 to 21.4 ft in desert alluvium to permit selection of the optimum depth of burst commensurate with crater size and shape and radioactivity release. Using the burst depth thus selected, four row shots, consisting of five 1,000-lb HE charges in each row, were fired with intercharge spacing varying from 1.0 to 1.5 apparent crater radii to determine the optimum spacing to produce a channel of satisfactory size and proportion and relatively free of irregularities. The immediate purpose of the experiment was to aid in the design of a proposed nuclear row-charge event (Project BUGGY).

Selection, fabrication, emplacement, and firing of the charges are discussed, along with the technique used to measure the apparent and true craters and zones of subsurface disturbance.

The selected depth of burst was 19.8 ft, or a scaled depth of approximately 180 $ft/kt^{1/3.4}$. The optimum charge spacing was determined to be about one and one-eighth apparent crater radii. Comparison is made with results of previous row-charge experiments, and graphs of channel parameters are developed. Channel depth was found to be very sensitive to charge spacing, but channel width varied only slightly with spacing. It is concluded that a usable channel with suitable dimensions can be excavated by means of nuclear explosives.

PNE 304 September 1963

PROJECT PRE-BUGGY: BASE SURGE ANALYSIS

Knox, J. B. and Rohrer, R. F.

This report summarizes and presents the data concerning the base surge cloud radius and base surge cloud height as a function of time for the Pre-BUGGY series of high explosive shots. An analysis of this information from the Pre-BUGGY sequency yields the development of empirical relationships between (a) the maximum base surge radius (cross wind) and the degree of atmospheric instability, and (b) the maximum base surge radius (cross wind) in a neutral atmosphere and the scaled depth of the

explosive in an alluvium medium. These two developed empirical relationships have important practical use for the preparation of predicted cloud geometries for future Plowshare events.

PNE 315F June 1965

STUDIES OF THE PRE-BUGGY II APPARENT CRATERS

Spruill, J. L. and Videon, F. F.

Five rows of five 1,000-lb charges and one row of thirteen 1,000-lb charges were detonated in the alluvial material at the Nevada Test Site. The charges were all fired at a depth of burst approximately 16% deeper than the optimum for radius for single charges except for two of the five-charge rows which were detonated approximately 32% deeper than optimum. For the five-charge rows, spacings of 0.94, 1.06, and 1.17 single charge crater radii were used. For the thirteen-charge row, spacings of 0.94, 1.17 and 1.40 single charge crater radii were used. The resulting craters showed that when the charges are spaced one single charge crater radius apart, the row crater averaged approximately 10% wider and 20% deeper than the crater from a single charge of the same weight detonated at the same depth, 16% deeper than optimum for single charge crater radius. At wider charge spacings, the row charge crater is both narrower and shallower. When the spacing is about 1.30 single charge crater radii, the width of the row crater is about the same as the diameter of the corresponding single charge crater. When the spacing is about 1.22 single charge crater radii, the depth of the row crater equals the depth of the single charge crater. The cross section of the row charge craters at the shallower of the two charge depths appeared to be more nearly hyperbolic than parabolic as has been commonly assumed for the single charge crater. For a depth of burst 16% deeper than optimum for radius, the greatest volume per charge is excavated when the spacing is about 1.125 single charge crater radii. The lips along the sides of the row craters averaged about 2.4 times the average height of the lips around the single charge craters from the same charge weight at the same depth of burst. However, the lips at the ends of the row craters were generally smaller than those of the single charge crater, and were quite irregular in vertical section. There appears to be an increase in the height of the lips along the sides of the row craters as the depth of burst is increased.

PNE 322 April 1969

PRESHOT GEOLOGIC AND ENGINEERING PROPERTIES INVESTIGATIONS—PROJECT BUGGY

Lutton, R. J., Hunt, R. W., and Rowland, R. E.

The site for the BUGGY row charge cratering event is located on Chukar Mesa, NTS, in dry basalt. Topography is relatively flat over an approximately square area

about 3,000 ft across. The site consists of about 330 ft of horizontal basalt flows resting on tuff breccia, other basalt flows, and a thich vitrophyric flow.

Unconfined compressive strengths tend to decrease with increasing porosity from 33,000 lb/in.^{2} for dense basalt to 6,200 lb/in.^{2} for vesicular basalt with 20 to 30% vesicles. Tensile splitting and unconfined and triaxial compression tests on dense basalt indicate a failure envelope with ϕ of 50 deg at normal stresses of 0 to 5,000 lb/in.^{2} and ϕ of 30 deg at normal stresses of 15,000 to 20,000 lb/in.^{2}. Cohesion is about 5,000 lb/in.^{2}. The Poisson's ratio for basalt ranges from 0.17 to 0.30 and is apparently not related to vesicularity.

The weighted lineal joint intercept spacing for near-surface basalt averages about 0.3 ft and that at depth averages about 0.9 ft.

Interlayered clinker zones apparently reduce the average seismic velocity of the medium by more than 50%.

PNE 501F November 1964

STEM DESIGN AND SHOTCRETE, GROUT, AND CONCRETE SUPPORT—PROJECT PRE-SCHOONER

Saucier, K. L.

Project Pre-SCHOONER consisted of four 20-ton chemical-explosive detonations in hard, dry rock at scaled depths of burst of 135, 160, 185, and 210 ft/kt$^{1/3.4}$. The primary purpose of the project was to increase the knowledge of crater dimensions in hard, dry rock as a function of depth of burst and type of explosive. This report describes the following work performed for the project by personnel of the U. S. Army Engineer Waterways Experiment Station (WES): (a) the design and placement of grout mixtures used in grouting satellite holes surrounding each ground zero location, (b) the design and supervision of the placement of a shotcrete mixture used in lining the walls of each of the shot cavities, and (c) the design and supervision of the placement of a concrete mixture used in stemming the access holes to each of the shot cavities.

PNE 502F March 1965

CRATER MEASUREMENTS—PROJECT PRE-SCHOONER

Spruill, J. L. and Paul, R. A.

In Project Pre-SCHOONER, four 40,000-lb spherical nitromethane charges were detonated at depths of burst of 42, 50, 58, and 66 ft in the basalt of Buckboard Mesa at the Nevada Test Site in February 1964.

Based upon the results of Project Pre-SCHOONER new cratering cruves for basalt have been developed. The depth of burst for maximum apparent crater radius and depth are 160 and 135 ft/kt$^{1/3.4}$, respectively. The deepest detonation Charlie, produced a mound of broken rock and earth that had a crater-like depression in its center entirely above the preshot ground surface. Average cross sections of the apparent

craters showed them to be hyperbolic rather than parabolic, with the average inclination from horizontal of the upper, approximately straight, slopes about 31 deg. A curve was also developed for apparent crater volume for basalt. Apparent crater volumes for craters in hard rock at depths of burst near optimum for radius may be predicted as

$$V_a = 0.4\ R_a^2 D_a.$$

Prediction curves were developed for apparent lip crest height and radius. For depths of burst near optimum for crater radius, lip crest heights and radii averaged

$$H_{al} = 0.2\ R_a$$

$$R_{al} = 1.4\ R_a.$$

Around the circumference of a single crater, lip crest height varied by about ±50% from the average. Outer edges of crater lips at depths of burst near optimum averaged between 4 and 5 apparent crater radii.

The extreme range of rock missiles decreased very rapidly with increasing depth of burst. A curve showing the variation of extreme rock missile range with depth of burst was developed. At near optimum depths of burst, the extreme missile range was about 20 apparent crater radii. The weights of rock missiles thrown to maximum ranges appeared to vary inversely with charge depth. For the shallower shots (at 129 and 155 $ft/kt^{1/3.4}$), the number of large missiles at maximum ranges indicated that a significant safety hazard exists.

PNE 503F April 1965

BASE SURGE AND CLOUD FORMATION — PROJECT PRE-SCHOONER

Rohrer, R. F.

This report summarizes the base surge cloud histories for the Pre-SCHOONER series of high explosive shots. An analysis of the data results in a correlation of the maximum base surge radius in a neutral atmosphere as a function of the scaled depth of the explosive in a basalt medium. The maximum base surge radius for explosions in basalt appears to be significantly less than those for comparable explosions in alluvium.

PNE 504F September 1965

STRONG MOTION SEISMIC MEASUREMENTS—PROJECT PRE-SCHOONER

Cauthen, L. J., Jr.

Strong motion seismograph stations were operated by the U. S. Coast and Geodetic Survey during the four Pre-SCHOONER cratering experiments conducted in basalt on Buckboard Mesa at the Nevada Test Site. The purpose of the strong motion experiments was to study the ground shock resulting from small-scale cratering detonations in hard rock. Surface acceleration and displacement time histories were recorded for each detonation at selected instrument stations.

The results of this study indicate that the ground shock resulting from the Pre-SCHOONER detonations (20-ton high explosive cratering detonations) differed from that observed from larger yield nuclear explosions. The most significant difference was in the attenuation rate of the surface acceleration which was higher for the Pre-SCHOONER detonations than has generally been observed for nuclear detonations. Also, surface displacements for the Pre-SCHOONER detonations were higher than would be predicted from previous nuclear surface displacements.

PNE 505P September 1965

PRESHOT INVESTIGATIONS FOR PROJECT PRE-SCHOONER, BUCKBOARD MESA, NEVADA TEST SITE

Nugent, R. C. and Banks, D. C.

A comprehensive geologic and engineering investigation was undertaken on Buckboard Mesa at the four sites selected for Project Pre-SCHOONER, a series of chemical explosive experiments conducted in dry basalt. This report covers the results of the preshot geologic and engineering investigation.

Subsurface conditions were determined from four vertical borings at each site: One centrally located 6-in.-diameter boring to a depth of 80 ft and three satellite NX core holes of variable depths at the ends of 35-ft radials that were spaced 120 deg apart. The sites are blanketed by a thin soil cover of rather uniform thickness, ranging from 2 to 4 ft at the four sites, overlying a basalt cap approximately 200 ft thick. The uppermost portion of this basalt cap is composed of vesicular basalt 25 to 50 ft thick which grades into underlying dense basalt 100 to 150 ft thick. The basalt is immediately underlain by 0 to 20 ft of ash or cinder beds.

A survey of the joint pattern at the Pre-SCHOONER sites disclosed four predominant high-angle sets, each set showing an extremely variable dip, and a fifth generally low-angle set of joints. The high-angle joint sets have the following preferred strikes: Set 1, N74°W; Set 2, N27°W; Set 3, N15°E; and Set 4, N62°W. The N15°E strike joint set is statistically predominant. The dip for each set tends to be vertical, horizontal, or 52 deg to either side of the strike. Jointing at Sites 4 and 7 is similar to the composite

joint pattern of the four sites, while Sites 3 and 11, although similar in many respects to the composite joint pattern, lack the strong development of the dominant strike set.

Contrary to borehole photography analysis, observations of the mesa walls disclosed that the high-angle joints were the most conspicuous. This discrepancy is due to the lesser probability of encountering high-angle joints when utilizing data obtained from vertical boreholes, thereby exaggerating the importance of low-angle joints. The nearly vertical high-angle joints were the most open fractures found on the mesa and also the most continuous.

Joint frequency curves derived for the Pre-SCHOONER sites indicate a rather uniform distribution in the vesicular basalt and a tendency to occur in groups in the dense basalt. In several instances the joints were spaced over 10 ft apart; however, about 53% of the joints were spaced less than 1 ft apart and about 94% less than 5 ft apart.

Engineering properties of the basalt were determined from static and dynamic laboratory tests conducted on 30 samples representative of the five different types of basalt at the Pre-SCHOONER sites and from geophysical logging at each site. The average physical property values of the foundation materials appear to be related to the vesicularity of the basalt.

Static unconfined compressive strength ranged from 18,000 lb/in.^{2} for dense basalt (Type I) to 7,000 lb/in.^{2} for the most vesicular basalt (Type V). Static unconfined compressive strengths for vesicular basalt Types III and IV were 117 and 185% greater, respectively, than the dynamic unconfined compressive strength of the same type basalt.

The angles of internal friction and cohesion for the basalt as determined from triaxial tests on intact samples were as follows: Type I dense basalt, ϕ = 45 deg, c = 4,520 lb/in.^{2}; Type IV vesicular basalt, ϕ = 28 deg, c = 1,720 lb/in.^{2}.

Dynamic tensile strengths of dense basalt Type I and vesicular basalt Type III were 16 and 30%, respectively, of the static compressive strength of the corresponding basalt types. Dynamic tensile strength of Type III basalt was 35% of its dynamic compressive strength; this value is higher than the normal ratio (10 to 20%) of tensile to compressive strength for rock and concrete.

The bulk specific gravity ranged from 2.73 for dense basalt to 2.36 for vesicular basalt. These values correspond to bulk densities of about 170 to 147 lb/ft^3, respectively. Corresponding in situ values calculated from neutron density logs were approximately 98% of these values.

Modulus of elasticity values determined by static tests were in good agreement with in situ values determined by three-dimensional logging. The range of in situ values was approximately 6×10^6 for dense basalt to 3×10^6 for vesicular basalt. Modulus of elasticity values determined by dynamic tests on the only two vesicular basalt types tested were approximately 30% greater than static test values from corresponding basalt types.

Poisson's ratio determined by dynamic tests during the investigation was in good agreement with a previously determined laboratory value of 0.20 for vesicular basalt.

In situ values as determined from three-dimensional logging were approximately 125% greater than the laboratory values.

The relation between Young's modulus of elasticity and shear modulus calculated from vibratory techniques at Sites 3 and 4 was similar to that obtained by three-dimensional logging; however, the values from vibratory measurements were about one-twentieth of those determined by three-dimensional logging. The discrepancy is attributed to the difference in direction and in the volume of material involved; the three-dimensional logging involved a relatively small volume of material in a vertical direction, whereas the vibratory techniques involved a large volume of material in a horizontal direction.

PNE 505F March 1967

GEOLOGIC AND ENGINEERING PROPERTIES INVESTIGATIONS—PROJECT PRE-SCHOONER

Lutton, R. J., Girucky, F. E., and Hunt, R. W.

The four Pre-SCHOONER high explosive cratering experiments were conducted in dry basalt on Buckboard Mesa, Nevada Test Site. The preshot and postshot conditions were investigated by core boring, borehole photography, geophysical techniques, aerial photography, and exploratory excavations. Representative core samples were tested in the laboratory for strength properties and specific gravity.

The rock consists of vesicular basalt over dense basalt, and each type is structurally modified by layering of vesicles resulting from viscous flow of the lava. Samples of dense basalt and highly vesicular basalt had saturated surface dry bulk specific gravities of about 2.75 and 2.35, respectively. Unconfined compressive strengths vary correspondingly from about 21,000 to 3,000 $lb/in.^2$ and Young's moduli lie in the range of about 1×10^6 to 7×10^6. Poisson's ratio by dynamic methods is about 0.18. Dynamic tensile splitting strengths averaged near 2,700 psi. In situ wet bulk densities range between 155 and 167 lb/ft^3.

Natural flow structure within the lava at the sites consists of flow-layered basalt types arranged as nested cylinders with gradational contacts. The axes of these cylinders parallel the flow direction inferred from topography. Cross folds are superimposed on the cylindrical structure. Joints and blast fractures tend to be parallel or perpendicular to flow layers, and as a result an anisotropy due to flow structure prevails at each site. This anisotropy appears to explain the conspicuously elliptical form at two of the craters.

In the two craters that were explored by trenching, the displaced ground surface was uplifted about 5 ft at the true crater. In the subsurface beyond the true crater at the Delta Site, zones of blast fracturing and bulking have been distinguished. These appear to be modified somewhat by the stratigraphy of the basalt. The limits of fracturing and bulking by the blast appear to lie at about 100 ft from the zero point.

PNE 506F October 1968

PROJECT PRE-SCHOONER: SURFACE MOTION MEASUREMENTS

Christopher, W. G. and Lattery, J. E.

Project Pre-SCHOONER consisted of four 20-ton nitromethane cratering detonations conducted by the United States Army Engineer Nuclear Cratering Group as part of the joint Atomic Energy Commission-Corps of Engineers nuclear excavation research program. The experiment was conducted in February 1964 in the basalt of Buckboard Mesa at the Nevada Test Site.

High speed photography and target markers were used to measure ground surface motions produced by each of the four detonations. Analysis of the surface motion data indicated that spalling was the principle crater-producing mechanism. The three detonations which produced apparent craters did, however, show varying amounts of second phase surface accelerations. Surface ground zero spall velocities ranged from 100 ft/sec for the detonation at a 66-ft burial depth (scaled depth of 236 ft/kt$^{1/3}$) to 170 ft/sec for the detonation at a 42-ft burial depth (scaled depth of 150 ft/kt$^{1/3}$).

PNE 507 December 1965

PROJECT PRE-SCHOONER II: TECHNICAL DIRECTOR's SUMMARY REPORT

Hughes, B. C., Benfer, R. H., Day, W. C., Larner, K. L., Heusinkveld, M., Marks, R. E., Rohrer, R. F., and Beers, R. F.

Project Pre-SCHOONER II was a chemical explosive single-charge cratering experiment conducted by the U. S. Army Engineer Nuclear Cratering Group as a correlation detonation for the Atomic Energy Commission's proposed Plowshare 100-kt SCHOONER nuclear cratering experiment. Pre-SCHOONER II was executed as a part of the joint AEC-Corps of Engineers nuclear excavation research program. The primary purpose of this experiment was to improve the knowledge of cratering in a hard, dry rock and to provide information which can be used in the emplacement design of the Schooner Event and in the assessment of the operational safety aspects of that event.

The Pre-SCHOONER II design consisted of a 100-ton liquid explosive nitromethane (CH_3NO_2) charge emplaced in a spherical cavity at a depth of 71 ft in the rhyolitic rock formation of the Bruneau Canyon region in southwestern Idaho. The charge was detonated on 30 September 1965 at 1709 MST. As a result of a leak which developed in the cavity, there were only 85.5 tons of nitromethane in the cavity at detonation time. This charge weight of nitromethane has an energy equivalent yield of 94.6 tons.*

*Based on the assumption that an energy equivalent yield of one ton releases 10^9 cal and that nitromethane releases 1220 cal/g of charge weight.

The crater produced by the detonation had an apparent crater radius of 95.2 ft and an apparent crater depth of 60.7 ft. The apparent crater volume was 24,780 yd^3, and the average lip crest height was 17.2 ft. The maximum range of missiles resulting from the detonation was 2320 ft.

The results of surface motion studies which were based on analysis of high-speed photography of the motion of a falling-mass target at Ground Zero (GZ) indicate that a peak spall velocity of 129 ft/sec occurred at GZ at 27 msec after zero time.

The results of the subsurface measurements program indicate that: (1) the signal time of arrival measurements and peak stress measurements in the horizontal direction from the shot point were in close agreement with the SOC computer calculation predictions; (2) the signal time of arrival and peak stress measurements in the vertical direction evidenced considerable scatter and were generally lower (for stress measurements) or occurred at a later time (for time of arrival measurements) than was predicted by the SOC calculation; (3) a peak positive vertical acceleration of 3000 g was measured by the accelerometer located near the upper surface of the rhyolite medium approximately 10 ft below the surface of the ground; and (4) the cavity pressure measurements, recorded over the time period that the fluid column functioned properly, agreed quite well with predicted measurements.

Strong motion measurements recorded at two stations, located 2.4 and 4.7 km east of GZ, produced acceleration data which agree quite well with predictions. The observed displacements at these two stations and the velocities recorded at four other stations located east and north of GZ were higher than predicted.

The following were maximum observed cloud dimensions: crosswind base surge radius, 2100 ft; base surge height, 1060 ft; main cloud radius, 875 ft; and main cloud height, 1400 ft.

Preliminary analysis of the close-in air blast measurements indicates that the ground-shock-induced pressures from the Pre-SCHOONER II detonation were twice those from previous cratering detonations at comparable scaled ranges. Analysis of the microbarograph measurements show that the average long-range air blast transmission factor for Pre-SCHOONER II was 0.19.

It should be noted that the observations, results, and conclusions outlined above are preliminary and subject to change based upon detailed analyses and interpretation of data. Final results will be presented in the reports listed in Appendix A.

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PROJECT PRE-SCHOONER II: APPARENT CRATER STUDIES

Benfer, R. H.

Project Pre-SCHOONER II was an 85.5-ton nitromethane detonation conducted by the United States Army Engineer Nuclear Cratering Group as a part of the Joint Atomic Energy Commission-Corps of Engineers nuclear excavation research program. The

charge was detonated on 30 September 1965 in hard, dry rhyolite rock at a depth of burst of 71 ft (scaled depth of 142 ft/kt$^{1/3.4}$ based on an energy equivalent yield of 94.1 tons). Surface Ground Zero was located approximately 40 mi southwest of Bruneau, Idaho.

Aerial stereophotogrammetric mapping and conventional field survey techniques were used to determine the apparent-crater measurements of the Pre-SCHOONER II detonation. The apparent-crater radius of 95.2 ft and depth of 60.7 ft are much larger than the values predicted using the basalt cratering curves (scaling power 1/3.4). The apparent crater has a volume of 24,780 yd^3 and the average profile is approximately hyperbolic.

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PROJECT PRE-SCHOONER II: PRESHOT GEOLOGIC AND ENGINEERING PROPERTIES INVESTIGATIONS

Lutton, R. J., Girucky, F. E., Hunt, R. W., and Curro, J. R., Jr.

The Pre-SCHOONER II site was selected, from five areas investigated, on the basis of refraction seismic surveying, core drilling, and surface mapping in extrusive igneous rock that generally models the nearby SCHOONER site. Bedrock below about 5 ft of stony silt consists of a 25-ft-thick layer of vitrophyre and vitrophyre breccia over felsite that extends to a depth of at least 150 ft. These two bedrock layers at the site have distinctly different physical properties, the felsite being relatively less porous and stronger in compression than the overlying vitrophyre. The felsite is massive at depth, although highly fractured, but it becomes steeply flow-layered in the upper portion. The flow layers continue across a gradational zone into the overlying vitrophyre. The resultant structure strikes about north 35 deg east. The felsite is conspicuously jointed, and the vitrophyre contains abundant microscopic cracks.

PNE 510 May 1967

PROJECT PRE-SCHOONER II: DESIGN, CONSTRUCTION, AND POSTSHOT EVALUATION OF CONCRETE STEM FOR ACCESS HOLE

Saucier, K. L. and Stewart, F. S.

Project Pre-SCHOONER II consisted of a 100-ton chemical explosive detonated in hard, dry rock at a depth of 71 ft. The primary purpose of the project was to increase the knowledge of crater dimensions in hard, dry rock as a function of depth of burst and type of explosive. This report describes the proportioning of a concrete mixture used in stemming the access hole of the shot cavity, the design of the stem configuration, laboratory tests conducted on core samples from the site and on specimens of the concrete mixture required for design of the stem, and placement of the concrete at the job

site. Based on observations of the detonation, fractured pieces of the reinforced concrete stem, and the size of the crater, it is believed that the stem acted effectively to stem the detonation.

PNE 511 February 1966

PROJECT PRE-SCHOONER II: CLOUD DEVELOPMENT STUDIES

Day, W.C. and Rohrer, R.

This report presents the cloud development data for the Pre-SCHOONER II high explosive cratering event conducted in a rhyolite medium in southwestern Idaho. Early base surge radius dimensions are given as a function of time in several directions, and are related to base surge cloud dimensions from past cratering experiments in alluvium and basalt. Measurements of base surge height, main cloud radius, and main cloud height are also given. Two new methods of cloud delineation are described: (1) a laser-radar technique, and (2) a fluorescent particle tracer technique.

PNE 512F September 1967

PROJECT PRE-SCHOONER II: AIRBLAST MEASUREMENTS

Reed, J.W. and Vortman, L.J.

Airblast resulting from detonation of 85.5 tons of nitromethane buried 71 ft in rhyolite rock was measured close-in, both along the ground and in a vertical field above the explosion, and also at long distances from the explosion. Close-in air-blast wave forms consisted of two positive pulses, the first induced by the ground shock and the second, larger, pulse from venting gas. Measured ground-shock-induced peak overpressures were larger than anticipated. Peak overpressures from venting gas likewise were larger—so much so that the system was over-ranged, resulting in loss of many of those peaks and degrading the results. A tentative overpressure and energy distribution in the field above the explosion was derived. Air-blast transmission to a large distance was about the same as experienced on other large HE explosions at comparable burial depths. Since the state of the art of neither close-in air blast nor large-range propagation was advanced appreciably, no significant conclusions are presented.

PNE 513 May 1968

PROJECT PRE-SCHOONER II: SURFACE MOTION MEASUREMENTS

Christopher, W.G. and Larner, K.L.

Project Pre-SCHOONER II was a small-scale high explosive (HE) cratering experiment conducted by the United States Army Engineer Nuclear Cratering Group as a part of the joint Atomic Energy Commission-Corps of Engineers nuclear excavation

research program. The 85.5 ton nitromethane charge was detonated on 30 September 1965 in hard, dry rhyolite rock at a depth of burst of 71 ft (scaled depth of 142 ft/kt$^{1/3.4}$ based on an energy equivalent yield of 94.1 tons). Surface ground zero (SGZ) was located approximately 40 mi southwest of Bruneau, Idaho.

As a result of this experiment, knowledge of the surface motion phenomena of a cratering detonation was extended to the rhyolite medium. Gas acceleration appears to have been a much more important cratering mechanism in rhyolite than it was in HE cratering detonations in either basalt or clay shale.

A peak spall velocity of 129 ft/sec occurred at SGZ 27 msec after zero time. Gas acceleration increased the SGZ velocity to about 220 ft/sec at the time of primary venting, 204 msec. The massive venting grew to a dome more than 200 ft wide at the time of total breakup of the material (about 600 msec after zero time).

The peak spall velocities of the surface motion targets relative to the radial distance from the zero point (ZP) decayed approximately as follows:

$$V_s \propto R^{-3.0} \propto \cos^{3.0} \theta_r$$

where

V_s = peak vertical spall velocity (ft/sec)

R = radial distance from ZP to preshot target position (ft)

θ_r = angle between vertical and line from ZP to preshot target position

The peak total velocities after initiation of the gas acceleration phase decayed essentially as:

$$V_t \propto R^{-3.3} \propto \cos^{3.3} \theta_r$$

where

V_t = peak total velocity after gas acceleration (ft/sec)

The magnitude of the Pre-SCHOONER II SGZ peak spall velocity was comparable to the spall velocity obtained from the DANNY BOY nuclear cratering detonation in basalt, but was much lower than velocities from comparable HE detonations in either shale or basalt. The Pre-SCHOONER II peak SGZ velocity at time of venting was higher than the peak velocities recorded for comparable nuclear or HE detonations in basalt or alluvium. The Pre-SCHOONER II peak SGZ velocity was somewhat lower than peak SGZ velocities observed during comparable HE cratering detonations in saturated clay shale.

PNE 514 April 1966

PROJECT PRE-SCHOONER II: GROUND SHOCK MEASUREMENTS

Davis, L. K.

An instrumentation plan was designed for the purpose of collecting seismic data which would be useful for making future predictions for the SCHOONER Event. Peak ground motions were predicted at each station so that instruments could be set at the proper recording levels. Good data were obtained at each station. The velocity data from six stations which employed tape recording were processed to remove the frequency dependency of the instrument response, and acceleration and displacement were derived from the corrected velocity recordings. Additionally, the velocity recordings were subjected to band-pass filtering and amplitude-frequency relations were obtained. The observed peak values of ground motion are presented in tabular and graphical form. Where appropriate, least-squares regression equations were fitted to the observed data. Comparisons of the observed data with the predictions show that in all but one case the predictions were low. The frequencies associated with the largest velocity amplitudes ranged from about 2 to 9 cycles/sec.

PNE 515 January 1966

PROJECT PRE-SCHOONER II: SUBSURFACE EFFECTS MEASUREMENTS

Heusinkveld, M. and Marks, R.E.

Subsurface effects measurements were made on the Pre-SCHOONER II Event, which was an 85-ton nitromethane cratering experiment in southern Idaho. Measurements attempted included subsurface stress, time of arrival of the stress wave, acceleration, subsurface spall phenomena, gas pressure in the expanding detonation cavity, and vertical subsurface motion.

The measured subsurface stresses were of essentially the same scaled amplitude as earlier results from SULKY and PALANQUIN, but were considerably lower than results from HARDHAT and SHOAL. Measured accelerations were higher in scaled amplitude than the results from DANNY BOY, but were lower than the results from HARDHAT. A subsurface spall was observed 8 m below the surface 18 msec after detonation time.

Early cavity pressure measurements were obtained, but the instrumentation failed before the time of greatest interest. The vertical subsurface motion experiment was unsuccessful.

PNE 516 September 1967

PROJECT PRE-SCHOONER II: POSTSHOT GEOLOGIC AND ENGINEERING PROPERTIES INVESTIGATIONS

Frandsen, A. D.

The Pre-SCHOONER II Event was a chemical explosive single-charge cratering experiment in hard, dry rock. The detonation was centered 71 ft below the ground surface and consisted of approximately 85.5 tons of nitromethane. The explosion produced a crater with an apparent radius of 95.2 ft and an apparent crater depth of 60.7 ft.

Postshot explorations of the crater consisted of excavating three radial trenches through the lip material and then extending two of the trenches into the fallback within the crater. Both bulk densities and block-size distribution of the ejecta and fallback were obtained. Bulk densities averaged 103.8 lb/ft^3 except for an anomolous value of 93.1 lb/ft^3 in one trench. Block sizes varied from fines of clay size to blocks greater than 6 ft in diameter.

The true crater radius and the lip upthrust were measured at the three trenches and averaged 100 ft and 11 ft, respectively.

The crater slope angles measured before, during, and after completion of the fallback excavation averaged 37, 42, and 38 deg, respectively.

PNE 527 June 1970

PROJECT SCHOONER: FAR-OUT FALLOUT COLLECTION PROGRAM FOR PROJECT SCHOONER

Tami, T. M. and Gibson, T. A., Jr.

The Far-Out Fallout Collection Program was an experimental program to collect and to analyze samples of long-range fallout from Plowshare nuclear cratering events. Samples of fallout from SCHOONER, a 31-kt cratering experiment, were collected at downwind distances ranging from 65 to 500 km from the detonation site. The field operations required to obtain the fallout samples and the radiochemistry techniques used to analyze the samples are described. Measured values of the gamma exposure rate resulting from fallout at downwind locations in eastern Nevada and western Utah are reported. The maximum recorded exposure rate 65 km from the detonation site was 130 mR/hr. Of the 80 fallout samples collected, 16 were radiochemically analyzed to determine the species and quantities of radionuclides, present. The presence in each analyzed sample of up to 20 different radionuclides, including ^{90}Sr and ^{131}I, was determined. The radiochemistry results are expressed in terms of deposited radioactivity per unit area (pCi/m^2).

PNE 601F March 1965

PROJECT DUGOUT: APPARENT CRATER STUDIES

Spruill, J. L.

Dimensions and geometry of the DUGOUT crater, produced by the detonation of a row of five 18,144 kg nitromethane charges in basalt, were analyzed. The linear portion of the crater was 41.6 m wide and 10.7 m deep, 36% wider and 53% deeper than the Pre-SCHOONER Alfa crater, which was produced by the detonation of an identical charge at the same depth. Lips on the sides of the crater were massive, and were about twice as high as those of the Alfa crater; on the ends of the crater the lips were slightly smaller than the Alfa crater lip. The volume per charge of the linear section of the crater was 70% greater than the volume of the Alfa crater. The greatest range of the rock missiles perpendicular to the row of charges was 2.5 times the greatest missile range from the Alfa detonation. To the ends of the row, rock missile ranges were about the same as for the Alfa detonation. The average cross section of the linear section of the DUGOUT crater was a hyperbola. Factors for the enhancement in row charge crater dimensions over those of the comparable single charge crater were generally larger than those developed from the Pre-BUGGY II row charges in alluvium.

PNE 602F December 1967

PROJECT DUGOUT: GEOLOGIC AND ENGINEERING PROPERTIES INVESTIGATIONS

Lutton, R. J.

The DUGOUT Event was a row cratering experiment in which five 20-ton nitromethane charges spaced 45 ft apart at depths of 59 ft in dry basalt were detonated simultaneously. The explosion produced an apparent crater about 135 ft wide, 285 ft long, and 35 ft deep. Preshot and postshot NX core and calyx hole drilling, trenching, laboratory analysis of core samples, and analysis of photographs have revealed preshot structure, the extent and characteristics of the ejecta and fallback, the zone of blast fracturing, the zone of bulking, and a sheared zone.

As revealed by preshot drilling, the upper basalt layer consists of about 40 ft of vesicular basalt overlying, with a gradational contact, about 50 ft of dense basalt. The vesicular basalt has been subdivided into four types on the basis of vesicle content and fabric. From 2 to 14 ft of silt overlies the bedrock.

Unconfined compressive strength for 6 samples ranges from about 7,000 to 17,000 $lb/in.^2$. Samples of dense basalt tested triaxially show a greater increase of strength with confining pressure than does a sample of vesicular basalt. Dynamic laboratory tests gave a compression wave velocity of 16,000 ft/sec for dense basalt and about 13,000 ft/sec for slightly vesicular basalt, and they indicated that Poisson's ratio averages about 0.25. Field seismic and vibratory studies indicate compression and

shear wave velocities of about 1,000 and 700 ft/sec, respectively, in the surface soil and 4,000 and 1,300 ft/sec, respectively, in highly vesicular basalt.

Flow layers complicating the otherwise simple stratigraphy form a system of nested cylinders with a mutual axis that parallels the direction of flow of the lava while it was still partly molten. Natural and blast-induced fractures have a preferred orientation parallel to flow layers. A second preferred orientation of joints is perpendicular to flow layers, but one major set of this group oriented normal to the cylinder axis is believed to be the dominant structural element modifying the crater process.

A more or less continuous blanket of ejecta extends as far as 500 ft (in one direction) laterally from the preshot position of the line of charges. This granular material has a bulking factor of about 1.39. In the subsurface, the zone of in situ bulking and the zone of blast fracturing extend laterally as far as 250 ft, but in detail there appears to be a concentration of fracturing at a depth of about 60 ft. A zone of shear deformation extends at least as far laterally from the row charge as 100 ft. In each of these three subsurface zones the intensity of deformation decreases outward.

The zone of blast fracturing along the projection of the row charge extends only about 160 ft from the end charge position, and the zone of shear deformation extends about 140 ft. A fourth zone characterized by relative displacement of points toward the crater with respect to points below is evident along the lip at the west end of the crater.

PNE 609F December 1964

PROJECT DUGOUT: DEEP UNDERGROUND SHOCK MEASUREMENTS

Day, J. D.

The objectives of the study reported herein were to study the underground transmission of shock from a row-charge cratering detonation and to evaluate the effect of such a detonation on adjacent charge emplacement holes.

The experimental layout consisted of ten 36-in.-diameter holes, drilled to a depth of approximately 64 ft in basalt on Buckboard Mesa at the U. S. Atomic Energy Commission's Nevada Test Site. These holes were drilled on 45-ft centers on an east-west line; the five easternmost holes were shot holes and the remaining holes were instrument holes. The five shot holes had a mined spherical cavity (approximately 10 ft in diameter) at the bottom with the center of the cavity at a depth of approximately 59 ft. These cavities were filled with a liquid charge, nitromethane. The instrument holes contained particle velocity gages and accelerometers; the diameters of these holes were measured before and after the shot in order to assess damage thereto.

The results of the gage measurements showed that the two instrument holes nearest the detonation were stressed beyond their elastic limits whereas the remaining three instrument holes survived and could have been used for later charge emplacement.

PNE 610F December 1964

PROJECT DUGOUT: CONCRETE, GROUT, AND SHOTCRETE SUPPORT, AND DESIGN AND POSTSHOT EVALUATION OF STEM

Saucier, K. L.

Project DUGOUT consisted of the simultaneous detonation of five, 20-ton, chemical, row-charge explosives in hard, dry rock at a scaled depth of burst of 185 ft/$kt^{1/3.4}$. The primary purpose of the project was to increase the knowledge of row cratering dimensions in hard, dry rock. This report describes the following work performed for the project by personnel of the U.S. Army Engineer Waterways Experiment Station: (1) the design and placement of grout mixtures used in grouting satellite holes surrounding the anticipated trench, (2) the design and supervision of the placement of a shotcrete mixture used in lining the walls of each of the shot cavities, (3) the design and supervision of the placement of a concrete mixture used in stemming the access holes to each of the shot cavities, (4) the design of the stem configuration for each of the five shot holes, and (5) postshot evaluation of stem design and survey of stem ejecta.

The stems designed for the project appear to have acted effectively. Apparently the lower part of the stems, from the reinforced concrete keys down, failed in compression and shear with the steel taking predominant shear stresses. Tensile spalling and bond failure were evident in the upper stem portions; however, there was evidence of conjugate concrete-basalt action in this area.

PNE 713F October 1965

PROJECT SULKY: CRATER MEASUREMENTS

Videon, F. F.

Project SULKY was the detonation of an 85-ton nuclear device in basalt at a depth of burst of 27.4 m. The detonation produced a mound of broken rock with a depression in the center. The base of the mound was roughly circular in plan and had a radius of 24.2 m. The radius of the crest of the lip around the ejecta was 8.87 m and the average height of the lip crest above preshot ground surface was 6.31 m. The bottom of the depression was 2.80 m above the preshot ground elevation. The preshot ground surface was uplifted and cracked to a distance of approximately 52 m from surface zero. The height of the upthrust was 1 m at the base of the rubble mound.

Based on the results of SULKY and other cratering data for basalt, the following conclusions have been made concerning cratering in hard, dry, inert rock:

(1) In the region of depths of burst somewhat deeper than optimum, nuclear explosives are less effective than high explosives for apparent crater production.

(2) Apparent crater dimensions diminish rapidly as the depth of burst increases beyond optimum.

(3) The apparent lip height, the true crater radii and the extent of upthrust beyond the true crater are similar for both nuclear and high explosive craters in basalt.

PNE 719P March 1965

PROJECT SULKY: PRESHOT GEOLOGIC INVESTIGATIONS

Nugent, R. C. and Banks, D. C.

A comprehensive geologic and engineering investigation was undertaken at the site on Buckboard Mesa selected for the SULKY Event, a nuclear cratering experiment, conducted in dry basalt.

Foundation conditions were determined by six borings: one centrally located, 6-in.-diameter boring to a depth of 80 ft and five NX-size holes ranging in depth from 59 to 212 ft. The site is blanketed by a thin soil cover of rather uniform thickness, ranging from 1.4 to 2.5 ft, overlying a basalt cap at least 192 ft thick. The uppermost portion of this basalt cap is comprised of vesicular basalt 47 to 72 ft thick (average 58 ft), which grades into an underlying dense basalt about 128 ft thick. The basalt is immediately underlain by approximately 14 ft of ash or cinder beds.

From the existing subsurface data, it is not possible either to confirm the existence of faults or to ascribe any differences in stratigraphy or lithology to faulting at the SULKY site. A survey of the joint patterns at the SULKY site disclosed four predominant high-angle strike sets, each set showing an extremely variable dip, and a fifth generally low-angle bedding or flow-layer joint set. The high-angle joint sets have the following average strikes: Set 1, N75°W; Set 2, N17°W; Set 3, N17°E; and Set 4, N41°E.

Contrary to borehole photography analysis, observations of the mesa walls disclosed that the high-angle joints are the most conspicuous. This discrepancy is due to the magnitude of the area observed; i.e., there is a lesser probability of encountering high-angle joints when utilizing data obtained from vertical boreholes, thereby exaggerating the importance of low-angle joints. The nearly vertical high-angle joints were the most open fractures found on the mesa and also the most continuous.

A joint frequency curve derived for the SULKY site indicates that although local fluctuations are present, no significant change in the frequency of joints occurs with depth. In several instances the joints were spaced over 10 ft apart; however, about 54% of the joints were spaced less than 1 ft apart, and about 97% were spaced less than 5 ft apart. The superimposed cumulative joint frequency curve for Pre-SCHOONER sites 3, 4, 7, and 11 indicated both curves to be quite similar, having the same median value (approximately 0.88 ft) and a closely paralleling relation. Based on investigations of DANNY BOY and Pre-SCHOONER, it is expected that the ejecta sizes will be closely related to the block size produced by jointing.

The average physical property values of the foundation materials as determined from geophysical logging are in close agreement with those determined in laboratory

tests, and appear related to the vesicularity of the basalt. The maximum average unconfined compressive strengths of sound specimens with no joints ranged from approximately 20,000 lb/in.^{2} for dense basalt to 10,000 lb/in.^{2} for the most vesicular basalt. The bulk specific gravity ranged from 2.74 for dense basalt to 2.40 for vesicular basalt. The modulus of elasticity varied from 4.48×10^6 to 7.66×10^6 lb/in.^{2}, with the values showing no particular relation to the degree of vesicularity. The values of physical properties as determined on the limited number of samples of basalt types from the SULKY site were all within the range of similar data scatter of an earlier study of Buckboard Mesa basalt.

The results of water pressure tests in drill holes NCG 10.4 and NCG 10.5 showed no evidence of any relation between the computed water-loss coefficient and the bulk porosity value of the rock as determined by gamma-gamma density logging. The average bulk porosity at the SULKY site was approximately 8%. The computed water-loss coefficient appears to be related to the effective porosity calculated on the basis of observed joint openings as indicated by the borehole camera.

PNE 720F September 1966

PROJECT SULKY: GEOLOGIC AND ENGINEERING PROPERTIES INVESTIGATIONS

Lutton, R. J. and Girucky, F. E.

The SULKY Event was a nuclear cratering experiment in which a device yielding 85 ± 15 tons was detonated at a depth of 90 ft in jointed basalt. The explosion produced a rubble-covered mound roughly circular in plan and extending approximately 24 ft above the original ground surface.

Prior to the event the SULKY site was explored by means of six core borings and the emplacement calyx hole. Geophysical logging was conducted and laboratory tests were performed on representative samples. Postshot investigations consisted of trenching through the mound, and drilling three core borings to determine the extent of the rupture zone.

The rock consists of vesicular basalt over dense basalt and each type is structurally modified by layering of vesicles resulting from viscous flow of the lava. Unconfined compressive strengths range from about 10,000 lb/in.^{2} for vesicular basalt to about 20,000 lb/in.^{2} for dense basalt. Bulk specific gravities for dense basalt are about 2.74, but with increasing vesicle content the bulk specific gravity reaches values as low as 2.40.

Two sets of axes of folds developed during flow of the lava are inferred from flow layer orientation. Subsequent natural joints tend to be parallel or perpendicular to this primary anisotropy and an orthogonal joint pattern emerges for most of the site. This natural pattern influenced the orientation of blast fractures, the orientation of surface fissures, the shape of the crater, and the distribution of rubble (ejecta and fallback) sizes.

The gross subsurface effect of the blast was development of a camouflet about 60 ft in diameter surrounded by a ruptured and dilated zone averaging about 200 ft in diameter. The limit of the dilated zone flares near the surface and in the center a chimney of the expanded media is inferred to have subsided and partially filled the camouflet.

PNE 904 April 1966

PROJECT PALANQUIN: STUDIES OF THE APPARENT CRATER

Videon, F. F.

Project PALANQUIN was a low yield nuclear detonation conducted by the Lawrence Livermore Laboratory as a part of the AEC Plowshare Program. The device was detonated in a porphyritic trachyte flow of the Ribbon Cliff Rhyolite formation, a hard dry rock, at a scaled depth of burst of 55.6 $m/kt^{1/3.4}$. Since the depth of burst was deeper than that which results in maximum apparent crater dimensions in rock, it was predicted that the detonation would result in a rubble mound rather than a crater below ground surface.

Detonation of the PALANQUIN device produced an apparent crater 72.6 m in diameter and 24.0 m deep. The production of an apparent crater was probably the result of scour by the escaping gas which vented prematurely. The asymmetry of the crater and the surrounding disturbance of the ground surface indicate the influence of geology in producing the crater. The crater is nearly hyperbolic in cross section, and the maximum inclination of the slopes of the crater walls is about 35 deg. The lip of the PALANQUIN crater resulted primarily from an upward displacement of the original ground surface. The distance to the edge of this uplifted zone is about twice the depth of burst. This extent of uplift agrees well with the results of the SULKY detonation (device detonated at scaled depth of 56.5 $m/kt^{1/3.4}$). The magnitude of the vertical displacement of the lip of the PALANQUIN crater, however, was less than that for SULKY.

PNE 905 June 1967

PROJECT PALANQUIN: PRESHOT GEOLOGIC AND ENGINEERING PROPERTIES INVESTIGATIONS

Nugent, R. C. and Girucky, F. E.

A comprehensive geologic and engineering investigation was undertaken at the site on Pahute Mesa selected for the PALANQUIN Event, a cratering experiment conducted in dry rock at the U. S. Atomic Energy Commission's Nevada Test Site.

Foundation conditions were determined by means of five borings satellitic to the emplacement hole: a 5-1/2-in.-diameter boring to a depth of 351.0 ft and four NX-size holes ranging in depth from 199.2 to 270.5 ft. The site is blanketed by a thin soil cover

ranging in thickness from 4 to 13 ft, overlying a 575-ft-thick section of the Ribbon Cliff formation. The uppermost flow of this formation is porphyritic trachyte, which is at least 351 ft thick beneath the site. The Ribbon Cliff formation is immediately underlain by the vitric tuffs and welded tuffs of the Timber Mountain Tuff.

Although normally a competent material, the porphyritic trachyte is severely altered and decomposed within zones of intense fracturing related to faulting.

Subsurface data indicate the presence of a high-angle normal fault that strikes N27°E and dips 64 deg to the northwest. This fault plane is enveloped by a zone of intense fracturing that is 73 ft thick. The base of this fracture zone parallels the fault plane and intersects the surface at a point 10 ft west of surface ground zero.

Field observations indicate that four high-angle joint sets are developed within the Ribbon Cliff formation—two major sets that have average strikes of N65°W and N55°E, and two minor sets that have average strikes of N16°W and N15°E. Low-angle bedding joints may be present locally. Joints of the dominant sets have an average spacing of less than 2 ft. Minor joint sets have spacings that vary from 3 to 10 ft. A comparison of surface observations with the results of a brief analysis of borehole photographs indicates a significant decrease in the frequency of joints with depth.

The average physical property values of the porphyritic trachyte are as follows: dry bulk specific gravity, 2.49; dry bulk density, 155 lb/ft^3; static unconfined compressive strength, 13,370 $lb/in.^2$; modulus of elasticity, 3.8×10^6 $lb/in.^2$; and Poisson's ratio, 0.26.

The static unconfined compressive strength tends to increase with increasing density values. The average bulk density in the upper 100 ft was approximately 2% lower than average density values below a depth of 150 ft.

Geophysical logging consisting of density and caliper logs disclosed that the in situ density values obtained were not quantitatively comparable to values determined in the laboratory due to the erratic variation in borehole diameter indicated by the caliper logs. Although it was not possible to establish the trend of in situ density with depth above a depth of 150 ft due to the erratic variations in borehole diameter, the trend of in situ density with depth below a depth of 150 ft appeared to approximate the trend indicated by physical tests; i.e., no major variation of density with depth.

Pressure tests indicated that permeability of the media at the PALANQUIN site was approximately 35×10^{-4} cm/sec near the surface and decreased to practically zero at a depth of 110 ft. No pressure test data were obtained between depths of 110 and 139.5 ft. Pressure test data obtained between depths of 139.5 and 203 ft were unreliable due to excessive head losses in the riser pipe. Between depths of 203 and 213 ft, the permeability was 27×10^{-4} cm/sec. No pressure test data were obtained below a depth of 213 ft.

PNE 957 October 1969

ENGINEERING PROPERTIES INVESTIGATIONS OF THE CABRIOLET CRATER

Frandsen, A. D.

The Project CABRIOLET nuclear cratering experiment was detonated in a hard, dry rock on Pahute Mesa at the Nevada Test Site. Bedrock at the site is classified as porphyritic trachyte, a rhyolitic type of extrusive igneous rock. The medium is fractured and vesicular in the upper part, but more dense and less fractured at depth. The preshot in situ density of the material within the true crater is estimated at 137 lb/ft^3

Investigations herein reported consisted of excavating a single tranch along a bearing of N18°E and determining the engineering properties of the ejecta material. The measured bulk density of the ejecta was 124 lb/ft^3 giving a bulking factor of 1.10. The average block size of the ejecta, as determined by mechanical screening, was approximately 0.12 ft (slightly less than 1-1/2 in.). The maximum uplift of the rupture zone observed in the excavated trench is 14 ft. The true crater radius as inferred from observations in the trench is 210 ft.

PNE 966 June 1967

PRESHOT GEOLOGICAL ENGINEERING INVESTIGATIONS FOR PROJECT CABRIOLET, PAHUTE MESA, NEVADA TEST SITE

Hunt, R. W., Bailey, D. M., and Carter, L. D.

The site of the CABRIOLET experiment is on Pahute Mesa, Nevada Test Site. The site media, explored by four borings, consist of porphyritic trachyte overlain by a thin soil layer. Fractured, vesicular zones in the upper portions of the borings yielded poor core recovery, while higher core recovery was obtained at depth in dense, less fractured rock. Flow layers strike approximately N35°E at the surface and impart a pronounced structural grain to the rock. At depth, most joints roughly parallel the flow layering and strike N20°E. Joint spacing ranges from less than 0.1 to greater than 10 ft.

Four high-angle faults are suspected in the vicinity of the site. Three of these strike roughly north-south and pass 200, 380, and 680 ft west of the site. The fourth inferred fault strikes approximately N63°E and passes 480 ft north of surface ground zero.

For dense, unfractured rock, the bulk density, saturated surface-dry basis, averages 158.5 lb/ft^3, while the bulk density, dry, averages 156.2 lb/ft^3. The porosity averages 4.5%, and the unconfined compressive strength averages 12,952 $lb/in.^2$. The vesicular material, based on one specimen, had a bulk density, saturated surface-dry basis, of 136.1 lb/ft^3, while the bulk density, dry, was 129.1 lb/ft^3. The porosity was 21.3%, and the unconfined compressive strength was 7,090 $lb/in.^2$.

PNE 1100 May 1968

PROJECT PRE-GONDOLA: SEISMIC SITE CALIBRATION

Kurtz, M. K., Jr. and Redpath, B. B.

Measurements of intermediate range ground motions and of structural response were made during the Pre-GONDOLA high explosive cratering experiments at Fort Peck, Montana. Liquid nitromethane charges (1000-lb and 20-ton), emplaced at various depths of burst, and a 140-ton row charge were detonated in the Bearpaw shale, which is a weak, wet clay-shale medium. An additional experiment to validate a charge emplacement concept designed to decouple seismic energy proved inconclusive. All seismic measurements were of particle velocity. Using an inverse power law equation to describe the attenuation of seismic amplitudes with distance, it is found that the amplitudes from the single charges decayed as approximately $R^{-2.4}$, and amplitudes from the row-charge decayed as $R^{-1.7}$. A dependence of amplitudes on depth of burst exists, and a yield scaling exponent near 0.8 appears to be appropriate.

It is suggested that a variation of particle velocity with distance as $R^{-A}e^{-kfR}$, where f is the signal frequency, is a more physically realistic description of attenuation than is the inverse power law. The preliminary data from the 140-ton row charge appear to fit this type of attenuation law, and indicate that A = 0.5 and k = 0.015 sec/km. An estimate is made of the near-source variation of peak seismic amplitude with frequency for the row charge, and predictions are made for possible future row-charge cratering experiments at the site.

PNE 1101 February 1967

PROJECT PRE-GONDOLA: SITE-SELECTION INVESTIGATIONS

Jack, H. A. and Dudley, W. W.

This report describes the site selection investigations for Project Pre-GONDOLA, a U. S. Army Engineer Nuclear Cratering Group chemical explosive cratering experiment in weak, saturated shale. The investigation was begun in January 1966 and concluded in June 1966 with the selection of an area adjacent to the Fort Peck Reservoir in northeastern Montana. In addition to an office study covering the U. S. and field reconnaissance of 14 sites, subsurface investigations with accompanying laboratory tests were conducted at the primary site and one alternate site near Edgemont, South Dakota. A second alternate site was considered at Cedar Ridge in Crook County, Wyoming, but no subsurface investigations have been conducted.

The medium present at the Fort Pack site is the Bearpaw shale, a highly compacted, uncemented clay-shale of Cretaceous age. The laboratory unconfined compressive strength of the intact shale is as great as 500 lb/in.^{2}, but the in situ field strength is reduced by bentonite seams and an extensive system of jointing and slumping. The medium is saturated, but its permeability is so low that free water is available to observation wells only where the shale is highly jointed. The site provides a variety of

terrain conditions which make it suitable for all phases of the experiment, including a row crater in varying terrain.

PNE 1102 May 1968

PROJECT PRE-GONDOLA I: TECHNICAL DIRECTOR'S SUMMARY REPORT

Kurtz, M. K., Jr.

This report presents the concepts, technical programs, objectives, and summarized results of Project Pre-GONDOLA I, a series of four 20-ton high explosive cratering experiments conducted during October-November 1966, near Fort Peck, Montana. The experiments established the cratering characteristics of the weak, wet, clay-shale (Bearpaw) preparatory to row-charge cratering experiments. The results were used in the design of the 140-ton Pre-GONDOLA II row-charge cratering experiment detonated on 28 June 1967.

The site medium, project layout, construction, field operations, and explosive charge design and emplacement are described.

Cratering calibration of the site was accomplished with four single 20-ton nitromethane detonations at depths of burst from 42.49 to 56.87 ft. Apparent crater radii varied from 80.4 to 65.1 ft and apparent depths from 32.6 to 25.2 ft. The craters produced were both deeper and wider than craters produced in alluvium and basalt and had flatter slopes. Optimum depth of burst for maximum crater dimensions was established as 130 $ft/kt^{1/3.4}$ for Bearpaw shale.

Surface motion velocities observed were higher than for any medium previously cratered. Peak surface ground zero velocities were significantly higher than those for high explosive craters in alluvium and nuclear craters in basalt, and were slightly higher than those observed for a high explosive crater in rhyolite (Pre-SCHOONER II).

A summary of preliminary results of engineering properties investigations is presented. Displacement studies indicate a movement of material in the region of the true crater boundary toward shot point.

Seismic data were obtained for both intermediate range ground motions and the response of the Fort Peck Dam, gate structure, and spillway. Predictions are made on the basis of these data for higher yield row-charge detonations. A depth of burst dependence for intermediate range ground motions was noted.

The clouds observed from the four detonations were unique. They were very diffuse, there were no main clouds, and steam was visible in the base surge clouds. Lidar tracking of the clouds was successful and indicated a capability to provide information as a function of time on the position, motion, growth, and internal structure of cratering explosion clouds.

The accumulated effects of the detonations were not injurious to fish in adjacent waters.

Final results of these studies not completed will be reported in the individual technical program reports listed in Appendix A.

PNE 1103 May 1969

PROJECT PRE-GONDOLA I: GEOLOGIC INVESTIGATIONS AND ENGINEERING PROPERTIES OF CRATERS

Fisher, P. R., Jack, H. A., and Kley, R. J.

This report presents the results of preshot and postshot geologic and engineering properties investigations performed in conjunction with the Project Pre-GONDOLA I cratering experiment series.

The Pre-GONDOLA I series consisted of the detonation of four 20-ton HE charges at varying depths of burst in highly over-consolidated Bearpaw clay shale at Fort Peck, Montana. The unweathered Bearpaw is a massive dark gray bentonitic clay shale with the following average physical properties:

Liquid limit	125
Plastic limit	27
Natural water content	19%
Degree of saturation	90 to 100%
Dry density	111 lb/ft^3
Bulk density	132 lb/ft^3
Unconfined compressive strength	250 $lb/in.^2$
Vertical preconsolidation pressure	32 $tons/ft^2$

Alluvial and glacial overburden materials of significant thickness were found only at the Bravo site. Depth of weathering at the four cratering event sites ranged from 9 to 15 ft. The weathered shale was fragmented near ground surface, becoming blocky with depth. The unweathered shale was moderately jointed. Free groundwater levels were variable and were significantly influenced by fracture permeability.

Detailed surface and subsurface postshot investigations were conducted at the Bravo crater. Surface postshot investigations only were conducted at the other crater sites. Pre-GONDOLA II preshot investigations provided postshot rupture zone information at the Charlie crater site.

The surface of the fallback and ejecta materials weathered markedly over the 7-mo period between the detonation data and the initiation of postshot investigations. Bulk densities and bulking factors of ejecta and fallback material at the Bravo crater were:

	Bulk density (lb/ft)	Bulking factor
Ejecta	109	1.18
Fallback	107-112	1.15-1.19

Significant permanent subsurface displacements and blast-induced fracturing extended to a distance of 250 ft, at ground surface, from the Bravo SGZ. Blast-induced fracturing extended to a distance of 400 ft from the Charlie SGZ.

PNE 1104 September 1967

PROJECT PRE-GONDOLA I: CLOSE-IN GROUND MOTION, EARTH STRESS, AND PORE PRESSURE MEASUREMENTS

Day, J. D., Murrell, D. W., and Sherman, W. C.

The objectives of this project were to measure and analyze the particle velocities, soil stresses, and pore water pressures produced by detonation of 20 tons of nitromethane in saturated clay-shale. The ground range of primary interest was 85 to 375 ft from surface ground zero with most instruments placed at shot depth (46.3 ft).

Peak stresses were greater than estimated at the close-in locations (8,000 to 12,000 lb/in.^{2} measured vs 5,000 lb/in.^{2} predicted) and attenuated as the -2 power with distance. Particle velocities were consistently higher than predictions based on experience in other media.

High amplitude transient pore pressures were produced by the explosion. Residual excess pore water pressures tended to drop off slowly with time.

PNE 1105 July 1967

PROJECT PRE-GONDOLA I: INTERMEDIATE RANGE GROUND MOTIONS

Power, D. V.

Ground motions were measured during the Pre-GONDOLA site calibration events and the Pre-GONDOLA I Events on Fort Peck Dam and free-field locations out to 95 km. These events included yields of 0.5 and 20 tons of high explosive detonated at various depths. A variation of peak ground motion with depth of burial was noted which indicated that peak motions from a completely contained explosion may be 1.5 to 2 times the motion resulting from an explosion placed at optimum depth for a cratering experiment. Attenuation with radius was found to be proportional to $R^{-2.45}$ for this region with at least one anomalous "hot spot" at 95 km north of GZ. Motions on the dam were comparable to free-field motions but vibrations persisted for longer times at the dam's natural frequency. Variation in motion was found to be proportional to the 1.0 power of the yield. Predictions for motions resulting from the Pre-GONDOLA II Event are made.

PNE 1106 August 1967

PROJECT PRE-GONDOLA I: STRUCTURES INSTRUMENTATION

Ballard, R. F., Jr.

Three microseismic stations were operated by the U. S. Army Engineer Waterways Experiment Station (WES) during the Pre-GONDOLA I cratering calibration series at Fort Peck, Montana. The seismic stations, located in the center of the dam, the Gate Control Structure No. 3, and on the spillway, were monitored for the purpose of

determining structure response resulting from the 20-ton charges detonated approximately 12 mi from the dam. Particle velocity data were recorded simultaneously on oscillographs and magnetic tape. Oscillograms were analyzed for maximum transient zero to peak particle velocities, and the tape was subjected to linear and power spectral density analysis from 0.5 to 20 Hz over a period of 160 sec.

The results of the study indicate that the amplitudes recorded during this test series exceeded the motions recorded during the 1000-lb calibration series by approximately 30 times at all stations. This report presents a documentation of test data.

PNE 1107 Part I December 1967

PROJECT PRE-GONDOLA I: CRATER STUDIES: CRATER MEASUREMENTS

Harlan, R. W.

Project Pre-GONDOLA I, a series of four 20-ton high explosive cratering detonations, was conducted by the U. S. Army Engineer Nuclear Cratering Group during October and November 1966 in order to determine the cratering characteristics of the Pre-GONDOLA project site located about 18 mi south of the town of Glasgow, Valley County, Montana. The essentially flat site medium consisted of uncemented, highly compacted, moderately jointed shale of the Late Cretaceous age, Bearpaw shale formation. The craters produced were both deeper and wider than those previously observed in either alluvium or basalt, but had flatter slopes. For single-charge craters in Bearpaw shale the optimum depth of burst for both apparent crater depth and radius is about 130 $ft/kt^{1/3.4}$. Pertinent data for the four events are summarized below.

Event	Energy equivalent yield	Depth of burst		Apparent crater radius		Apparent crater depth	
	tons	ft	$ft/kt^{1/3.4}$	ft	$ft/kt^{1/3.4}$	ft	$ft/kt^{1/3.4}$
Charlie	21.58	42.49	131.2	80.4	248.0	32.6	100.7
Bravo	21.30	46.25	143.4	78.5	243.4	29.5	91.5
Alfa	22.39	52.71	161.1	76.1	232.5	32.1	98.1
Delta	22.26	56.87	174.0	65.1	199.3	25.2	77.1

PNE 1107 Part II February 1969

PROJECT PRE-GONDOLA I: CRATER STUDIES: SURFACE MOTION

Christopher, W. G. and Lattery, J. E.

Project Pre-GONDOLA I was a series of chemical explosive, single-charge cratering experiments in weak, wet clay shale conducted by the U. S. Army Engineer Nuclear Cratering Group as a part of the Joint Atomic Energy Commission-Corps of Engineers nuclear excavation research program. The four 20-ton (nominal) charges

were detonated during the period 25 October to 4 November 1966, near the edge of Fort Peck Reservoir approximately 18 mi south of Glasgow, Montana.

Motions of the ground surface were measured by high-speed photography of surface targets which had been positioned as far as 96 ft from each surface ground zero (SGZ). The results indicated that the maximum SGZ velocities recorded for these detonations were larger than those for cratering detonations in other media at comparable scaled burial depths. The four Pre-GONDOLA I detonations produced maximum SGZ velocities of 255, 200, 167, and 139 ft/sec for scaled burial depths of 152, 167, 187, and 202 $ft/kt^{1/3}$, respectively. Maximum resultant surface velocities for the three shallowest detonations varied approximately as the -2.2 power of the radial distance from the charge. The maximum resultant surface velocities for the deepest detonation varied approximately as the -2.9 power of the radial distance from the charge.

PNE 1108 September 1967

PROJECT PRE-GONDOLA I: CLOUD DEVELOPMENT STUDIES

Day, W.C. and Rohrer, R.F.

The clouds resulting from four 20-ton nitromethane cratering explosions in a wet clay shale medium were studied by photographic analysis and lidar (laser-radar) tracking. A technique for detecting tracers in future events in the same medium was investigated.

It was found that the clouds were unique in that (1) they were very diffuse (low particle density) and ceased to be visible within several minutes, (2) there were no main clouds resulting from dynamic venting during mound rise, and (3) steam was visible in the base surge clouds. Base surge radius dimensions observed were larger than those observed in basalt and smaller than those observed in alluvium. Base surge height dimensions were much larger than those previously observed in any medium due to the steam present in the cloud.

Lidar tracking was successful and indicated its capability to provide information as a function of time on the position, motion, growth, and internal structure of cratering explosion clouds.

Cloud sampling indicated that several elements including palladium, cadmium, indium, and europium are suitable for use as tracers in future chemical explosive cratering events at the Pre-GONDOLA I site.

PNE 1110 July 1967

PROJECT PRE-GONDOLA I: LIDAR OBSERVATIONS OF THE PRE-GONDOLA I CLOUDS

Oblanas, J.W. and Collis, R.T.H.

This report describes lidar (laser radar) observations of the dust and steam clouds that resulted from the Pre-GONDOLA I series of four chemical explosions made near Fort Peck Reservoir, Montana, during October-November 1966. The neodymium

lidar was well able to track the clouds even when they became too tenuous to be seen visually or photographed.

Observational data were analyzed to obtain cloud dimension, height, volume, rate of growth, volume backscatter coefficient and relative density variations.

It is concluded that lidar tracking techniques can provide unique information on the position, motion, rate of growth, and internal structure of visible and subvisible clouds resulting from large-scale explosions, and recommendations are made for improving the operational efficiency of the technique.

PNE 1111 July 1967

PROJECT PRE-GONDOLA I: PRESHOT GEOPHYSICAL MEASUREMENTS

Stearns, R. T. and Rambo, J. T.

A series of preshot downhole geophysical measurements was performed at three out of the four locations on the Pre-GONDOLA I site near Glasgow, Montana. These in situ measurements in nearly homogeneous shale included density, gamma ray-neutron, caliper, electric, three-dimensional velocity, continuous velocity and seismic uphole-downhole logging.

All measurements except gamma ray-neutron and electric logging appear to have yielded useful quantitative data. Average densities ranged from 2.11 to 2.42 g/cm^3, and average velocities fluctuated between 1732 and 2014 m/sec below the weathered zone. Density measurements performed by the U. S. Army Engineer, Omaha District, compared favorably with those made by LLL.

An opportunity to compare in situ sonic velocities made by three different tools in the same hole showed a variation in measured value with the method used. These data suggest that the distance between wave source and detector is responsible for the variation in measured velocity.

PNE 1112 February 1971

PROJECT PRE-GONDOLA II: SUMMARY REPORT

Day, W. C., Kurtz, M. K., Jr., Steinhardt, G. C., Lattery, J. E., Frandsen, A. D., Redpath, B. B., Cress, J., Keefer, J. H., Jackson, W. F., and LeFevre, D. P.

This report presents the design concept, the objectives, the technical programs and the summarized results of Project Pre-GONDOLA II. Project Pre-GONDOLA II resulted in the first of a series of three interconnected, linear, explosively excavated craters. It was performed as an experiment in explosive excavation in a saturated clay shale, adjacent to the Fort Peck Reservoir, Fort Peck, Montana on 28 June 1967.

The site medium, the project layout, the explosive charge design, and the emplacement are described.

Five spherical charges of nitromethane, three at 20 tons each and two at 40 tons each were emplaced at depths ranging from 48.8 to 59.9 ft and spaced approximately

80 ft apart. The charges were simultaneously detonated to produce a crater that connected to a previously excavated 20-ton crater. The resulting linear crater was 490 ft long. The width of the crater varied from 142 to 214 ft. The apparent depth varied from 34 to 57 ft.

Surface motion spall velocities of 145 to 215 ft/sec were measured at and between surface ground zeros. A poorly defined gas acceleration phase increased these velocities to maxima ranging from 190 to 230 ft/sec, except for the ground directly over one of the 40-ton charges. Over this charge the maximum velocity reached 260 ft/sec. A trench excavated through the crater lip indicates a maximum uplift of the original ground surface of about 8 ft. Some uplift extended as far as 250 ft from the centerline of the row. Subsurface displacements in the same region were determined and show a good correlation with maximum ground stress measured during the detonation.

Seismic amplitude attenuation was determined to be proportional to the frequency of the motion, and an attenuation law based on this fact was derived. A seismic amplitude yield scaling factor of $W^{0.8}$ was determined for the row detonation when compared to the Pre-GONDOLA I detonations of 20 tons each.

Peak air overpressure consisted almost totally of the ground-shock-induced portion of the signal, the gas vent portion having a maximum amplitude of about an order of magnitude lower than the ground-shock portion. Peak air overpressure was found to be inversely proportional to the first power of the distance from surface ground zero. The overpressures normal to the row orientation were about 50% greater than those at the same distances off the end of the row.

The cloud was similar to those observed on previous 20-ton detonations in clay shale. The average base surge radius was 1266 ft and the height was 800 ft. There was no visible main cloud. A laser radar cloud tracking system (lidar) operated from an aircraft, was successfully tested.

The Pre-GONDOLA II detonation-generated shock wave was apparently not harmful to fish in the adjacent reservoir.

Detailed results and interpretations for all of these technical programs are presented in the report.

PNE 1113 October 1968

PROJECT PRE-GONDOLA II: CLOSE-IN GROUND MOTION AND EARTH STRESS

Joachim, C. E.

Stress, particle velocity, and acceleration data were obtained from a 140-ton nitromethane row-charge detonation in a saturated clay-shale. The charge row consisted of two 40- and three 20-ton spheres (first and fourth charges were 40 tons) extending S 11 W from the Pre-GONDOLA I Charlie crater on an 80-ft spacing (first charge 105 ft from crater center). The primary instrument line (stress and particle velocity gages) extended S 79 E from the center charge (G) with gage stations 100, 150, 200, 300, and 400 ft from G. Gage depths were 10 and 50 ft except the 400-ft station

which was gaged at 50 ft only. Acceleration measurements were made on the slopes of the Pre-GONDOLA I Delta and Charlie craters and at the Control Point (CP).

Peak stress measurements were higher than Pre-GONDOLA I data. As the charge-to-gage distance increased, the individual compressional waves from the various charges began to coalesce. The resulting stresses (coalesced wave) scale using combined charge weights and cube root scaling.

Initial peak horizontal velocity compares well with Pre-GONDOLA I data. Similar to stress, velocities resulting from the coalesced shock front scale using cube root.

PNE 1114 April 1970

PROJECT PRE-GONDOLA III, PHASE I: SUMMARY

Cress, J. P., Lattery, J. E., Andrews, J. B., Warden, F. F., and Vortman, L. J.

Project Pre-GONDOLA III, Phase I, a continuation of chemical-explosive cratering experiments conducted in saturated clay-shale near Fort Peck, Montana, was designed to excavate a row crater with relatively flat side slopes. This was accomplished by detonating three parallel row charges, each row containing seven 1-ton charges of nitromethane. The two outside rows were detonated as the first pass, and the center row was detonated as the second pass. The final apparent crater had a width of 169 ft, a depth of 11.2 ft, and average slopes of 1 on 5.4.

The technical programs conducted during the experiment were: (1) measurements of the apparent crater, (2) surface-motion analysis, (3) cloud-development studies, and (4) airblast measurements.

PNE 1115 October 1968

INTERMEDIATE RANGE GROUND MOTIONS FOR PRE-GONDOLA II AND ASSOCIATED EVENTS

Power, D. V.

Ground motion records from seven high explosive cratering events in northeastern Montana were analyzed for peak velocity, power spectral density, and velocity spectra. The events included four 20-ton single charges at depths of burst which varied from 42 to 57 ft, a 140-ton row charge consisting of three 20-ton charges and two 40-ton charges at optimum depths of burst, and a fully coupled charge of 0.5 ton and a decoupled charge of 0.5 ton at optimum depths of burst. It was found that at these depths and charge weights an increase in depth of burst resulted in an increase in peak velocities and power spectral densities as measured at distant points (>5 km), while no significant frequency shifts were noted. Power spectral density was found to be approximately proportional to the first power of yield. For this region it was determined that power spectral densities varied inversely as radius to the 3.55 power, and peak velocities and power spectral densities for small decoupling factors was found to occur for a certain explosive-cavity configuration. Three analysis techniques, peak velocity,

velocity spectra, and power spectral density, are compared and it is shown that power spectral density is the most consistent method when comparing records from different measuring stations.

PNE 1116 May 1968

PROJECT PRE-GONDOLA II: STRUCTURES INSTRUMENTATION

Ballard, R. F., Jr.

Five seismic recording stations were operated by the U. S. Army Engineer Waterways Experiment Station (WES) during the Pre-GONDOLA II 140-ton row-charge experiment at Fort Peck, Montana. Amplitudes of 10^{-2} to 10^{-1} cm/sec peak velocity were recorded at seismic stations located near the center of the dam, in the reservoir, Gate Control Structure No. 3, Powerhouse No. 2, and on the spillway. Amplitudes predicted on the basis of earlier 0.5- and 20-ton experiments were moderately low. The yield scaling exponent was increased from 0.67 to 0.75 to increase the accuracy of the structure response prediction equation. Magnetic tapes were subjected to RMS time history and power spectral density analysis from 0.5 to 20 Hz over a period of 160 sec.

PNE 1117 September 1970

PROJECT PRE-GONDOLA III, PHASE II: SUMMARY REPORT; CONNECTING ROW-CRATER EXPERIMENT

Lattery, J. E., Steinhardt, G. C., Anderson, B. D., Andrews, J. B., Redpath, B. B., Reed, J. W., and Ballard, R. F., Jr.

Project Pre-GONDOLA III, Phase II was a row-crater experiment conducted on 30 October 1968 by the U. S. Army Engineer Nuclear Cratering Group at a site near Fort Peck, Montana. The primary experimental objective was to form a row-crater which would smoothly connect to the crater formed by a previous row-charge detonation, Pre-GONDOLA II.

The row-charge consisted of seven 30-ton charges of nitromethane. These were emplaced in the clay-shale medium at depths averaging 53 ft with a typical horizontal spacing of 86 ft. Several technical programs by various governmental agencies and contractors measured the crater and significant side effects of the detonation.

The detonation produced a crater having an apparent length of 610 ft, an average width of 191 ft, and an average depth of 48 ft. In combination with the preexisting crater, it formed a linear crater approximately 1100 ft in length.

Technical programs were implemented (1) to measure motions of surface ground zero, (2) to compare preshot and postshot hydrologic, lithologic, and physical conditions of the site and cratered area, (3) to measure long-range airblast, (4) to determine the size and form of the dust cloud, (5) to measure intermediate-range seismic motions, and (6) to measure induced motions of the Fort Pack dam and associated structures. The final results and analyses are presented for all except the long-range airblast program. Final results for this last will be reported separately.

PNE 1118 June 1971

PROJECT PRE-GONDOLA III, PHASE II: MICROBAROGRAPH MEASUREMENTS

Reed, J. W. and Day, W. C.

Four microbarograph stations recorded waves at about 130 mi range from a row-charge of high explosives buried near optimum cratering depth. Comparison with propagations from three airburst calibration detonations showed that a source model derived from close-in data was appropriate for distant effects predictions. This model predicted that wave amplitudes from explosives at this scaled depth would be 20% of amplitudes expected for a free-airburst. All amplitudes perpendicular to a row charge are proportional to the 0.7 power of the number of charges in the row.

PNE 1119 November 1967

PROJECT PRE-GONDOLA II: AIRBORNE LIDAR OBSERVATIONS

Collis, R. T. H. and Oblanas, J. W.

Lidar (laser radar) observations from an aircraft of the cloud of debris resulting from the Pre-GONDOLA II explosion at Fort Peck, Montana, are described. With the neodymium (near infrared) lidar pointing horizontally at 45 deg aft of the aircraft beam, the aircraft made a series of flights past the cloud position at a height of approximately 225 m above ground level and the lidar was fired at intervals of approximately 6 sec. Since the cloud rapidly became invisible, these flights were positioned with reference to the lidar observations using a Doppler navigation system. From the lidar observations the location, shape, and internal structure (in terms of variations of density) of the cloud at the flight level were determined at five successive times, extending some 37 min after the explosion and some 17 km downwind. While this technique is thus shown to be immediately available (with minor improvements) for limited operational application, the developments necessary to realize its full potential are identified and described. In particular, significant improvements in the data handling system are proposed.

PNE 1120 August 1971

PROJECT PRE-GONDOLA III, PHASE III: CONNECTION OF A ROW CRATER TO A RESERVOIR (also published as TR-38, which see for abstract).

Redpath, B. B.

PNE 2000 September 1964

ISTHMIAN CANAL PLANS—1964: ANNEX C, APPENDIX 1, NUCLEAR EXCAVATION PLAN

Graves, E., Jr., Nordyke, M. D., and Cauthen, L. J., Jr.

This appendix describes a plan for using nuclear explosions to dig the channel for an Isthmian sea-level canal. It considers two alternative routes: the Sasardi-Morti Route, also known as Route 17, in the Darian region of eastern Panama and the Atrato-Truando Route, also called Route 25, across the northwest corner of Colombia. The nuclear excavation would be carried out in conjunction with the general construction described in Appendix 2 in order to complete a fully operating canal.

The current restudy of nuclear methods has reaffirmed the basic technical concepts of the earlier study. Because the current study has been more detailed, it has resulted in a greater appreciation of the limitations of our present information. The report emphasizes the development and site surveys needed to improve the estimates of cost and safety.

The nuclear excavation plan for the Sasardi-Morti Route in Panama calls for detonating 294 nuclear explosive devices with an aggregate yield of 166.4 Mt, to be fired in 14 separate detonations. The part of the Atrato-Truando Route in Colombia selected for nuclear excavation would require 262 nuclear devices with an aggregate yield of 270.9 Mt, to be fired in 21 detonations. For either route the main hazards from radioactivity, airblast, ground shock, throwout, and dust would be handled by evacuating the area around the explosions. An estimated 30,000 people would have to be moved from the vicinity of either route and resettled in adjacent frontier areas. More research and site data are needed to resolve all questions about hazards beyond the evacuation area. At these greater distances the possible hazards are not severe, and the outlook for control is promising. The cost of the nuclear excavation, including emplacement drilling, area excavation, charges for nuclear explosives, and nuclear operations, but excluding supporting general construction, is estimated to be $307,000,000 for the Panamanian route and $315,000,000 for the Colombian route.

PNE 2001 September 1964

ISTHMIAN CANAL STUDIES—1964 INCLOSURE A—EXCAVATION WITH NUCLEAR EXPLOSIONS

Graves, E., Jr., Nordyke, M. D., and Cauthen, L. J., Jr.

This inclosure describes the design of the nuclear explosions required to excavate the channel for an Isthmian sea-level canal. It begins with a summary of cratering technology and the procedures for designing a nuclear cut. This information is applied to two alternative sea-level canal routes across the American Isthmus: the Sasardi-Morti Route (Route 17) across the Darien region in eastern Panama and the Atrato-Truando Route (Route 25) across the northwest corner of Colombia. Data are developed on the number of each size nuclear device required, the emplacement condi-

tions, the predicted dimensions and stability of the nuclear cut, the combination of devices to be fired simultaneously in each detonation, and the drilling program to provide emplacement holes for the nuclear explosives. Problem areas in the design resulting from gaps in nuclear cratering technology and site data are identified and evaluated in order to provide guidance for nuclear development and on-site surveys. Subject to the limitations of available information, it is concluded that the nuclear cut for the Panamanian route would require 294 nuclear explosive devices with a total yield of 166.4 Mt, to be fired in 14 separate detonations. The Colombian nuclear cut would use 262 devices with a total yield of 270.9 Mt, fired in 21 separate detonations.

PNE 5001P July 1964

ENGINEERING GEOLOGY OF BUCKBOARD MESA, NEVADA TEST SITE

Banks, D. C. and Saucier, R. T.

The U. S. Army Engineer Waterways Experiment Station (WES) was requested by the U. S. Army Engineer Nuclear Cratering Group (NCG) in June 1963 to conduct investigations for the purpose of selecting five sites suitable for cratering experiments in the basaltic material found in the portion of the Nevada Test Site known as Buckboard Mesa. WES personnel were responsible for accomplishing the geologic reconnaissance and all preshot subsurface explorations for location of the five sites, four of which were later to be designated as sites for the Pre-SCHOONER Project and the fifth held in abeyance for the SULKY Project.

After five sites had been located and the presence of basalt of adequate thickness and quality established by borings, the NCG decided that attempts should be made to locate additional sites in the same general area for other Project PLOWSHARE cratering events (e.g. DUGOUT, SULKY). As a result, the drilling program was expanded appreciably beyond that originally planned for Project Pre-SCHOONER. Concurrently, data were obtained regarding the physical properties of the basalt in the Buckboard Mesa area from laboratory examinations and geophysical logs.

By October 1963, a considerable volume of geologic and test data had been compiled for the Buckboard Mesa area, including results of earlier (1960) investigations for Project BUCKBOARD conducted by the U. S. Geological Survey (USGS) and initial WES postshot investigations at the Project DANNY BOY site. As a result of having assembled these data, the WES was asked by the NCG to prepare a report embodying the data plotted during the various site selection studies and preshot and postshot investigations pertaining to all cratering studies on Buckboard Mesa. The draft report was received by NCG, and the WES was asked to present the data contained therein in the form of a published interim report for a wider distribution. This report is the result of that request.

In view of the volume of material contained herein and the continuing acquisition and analysis of data, it was deemed advisable at this time to simply present, and make only a tentative evaluation of the data. These data will serve as a basis for a future

final report on Buckboard Mesa, and for subsequent detailed reports on specific sites and events in which final evaluations and conclusions will be reached.

PNE 5003 February 1965

INVESTIGATION OF MANUFACTURE OF AGGREGATE AND RIPRAP BY NUCLEAR MEANS

Polatty, J. M., Houston, B. J., Stowe, R. L., and Banks, D. C.

The objectives of the work reported herein were to investigate the feasibility of producing aggregate and riprap by nuclear means and to verify and supplement size distribution data obtained by a photogrid method. This was accomplished by determining the size distribution, density, absorption, abrasion resistance, shape characteristic, rock types, and degrees of new fractures of material from 16 piles of ejecta from a trench excavated into the lip of the DANNY BOY crater. Particle sizes were estimated by comparisons with the 1-ft grid spacing. Results of tests indicate that approximately 10% of the ejecta could be used for concrete aggregate after proper separation without secondary crushing. Physical tests and geologic examinations confirm that this ejecta would be acceptable as concrete aggregate. Thirteen percent of the ejecta was in the size range needed for riprap. Fracturing of the ejecta was minor, and the dense particles would make good riprap. All ejecta could be used with moderate sizing for jetty stone. The photogrid method indicated that the material was coarser than shown by mechanical separation, though a direct comparison may not be valid in this case since different areas of the deposit may have been analyzed. However, because of the speed and low cost of the photogrid method, further study is warranted.

PNE 5004F April 1969

CONSTRUCTION TECHNIQUES AND COSTS FOR UNDERGROUND EMPLACEMENT OF NUCLEAR EXPLOSIVES

Hair, J. L.

This report describes the equipment, methods, and costs that are considered applicable for underground emplacement construction of nuclear explosives such as would be used in nuclear excavation.

The text of the report discusses the available methods and techniques currently being used in "big hole" (30-in. diameter and larger) drilling, tunneling, and conventional shafting. The technical data have been collected from the available literature as well as by personal contacts with the Government agencies and private industries concerned.

Big hole drilling methods can be divided into four types: churn drilling, auger drilling, calyx drilling, and rotary drilling. Of these, auger drilling is the most economical for holes to depths of 200 ft in soft material, and rotary drilling is by far the best choice for depths in excess of 150 ft. Rotary drilling is not limited to any specific

material type or hole size and therefore is the most adaptable method. Equipment for rotary drilling is variable, but in most cases consists of "beefed-up" oil well rigs employing modified hoisting facilities. The drill strings, drill bits, and circulating equipment are ordinarily designed specifically for big hole work. Typical input power ratings for the rigs range from 225 hp (drive-in rigs) to 1625 hp (stationary rigs), depending on the diameter and depth of hole. Borings from 36 to 72 in. in diameter are currently being drilled to depths exceeding 6000 ft with modified oil-well drilling equipment.

Discussions of mining and shafting include the conventional cyclic method of drilling and blasting as well as the mechanical mining methods, which in the past few years have gained considerable popularity. With the cyclic method the average rate of advance for tunnel bores 8 to 12 ft in diameter appears to be about 10 to 12 ft per 8-hr shift, assuming average rock conditions. Average rate of advance for 2- to 3-compartment shafts appears to be about 6 to 8 ft/day.

Mechanical tunneling methods are currently being used with much success in both soft and hard rock. Various new equipment has become available with emphasis being placed on increasing the thrust capabilities of the cutter heads and improving the design of the cutters. Rate of advance for mechanical mining is variable depending on rock hardness; it appears to range from 8 to 10 ft/hr in soft rock and 2 to 5 ft/hr in hard rock.

Procedures which can be used to make preliminary cost estimates for drilling large diameter holes are included in Appendix A. The data from which to make these estimates are in the form of cost and performance curves constructed from current price and practice schedules as furnished by drilling companies and equipment manufacturers presently active in "big-hole" drilling.

Appendix B consists of three parts. Part 1 is an analysis of conventional tunneling costs, Part 2 is an analysis of mechanical tunneling cost, and Part 3 describes the cost factors involved in sinking shafts by conventional methods. These data are considered adequate for estimating guidelines only. Any comprehensive estimating of tunneling costs should be prepared by use of established techniques.

A brief summary of the equipment requirements and costs necessary to rotary drill large diameter holes to depths of approximately 5000 ft are outlined in Appendix C. This depth range was not included in the original study request and the information presented in this report was, by necessity, assembled from a minimum of research.

PNE 5005 August 1966

PROJECT DANNY BOY: ENGINEERING GEOLOGIC INVESTIGATIONS

Nugent, R. C. and Banks, D. C.

Preshot and postshot investigations of the DANNY BOY site were made to obtain information on the change in engineering properties of the basalt media adjacent to the

crater and to determine engineering properties of the important physiographic features of the crater such as ejecta and fallback materials. Field investigations included geological studies of the area and core borings in which borehole photographs were made and water pressure tests were conducted. Particle size distribution and density of the ejecta materials were determined.

Preshot geologic investigations were conducted by the United States Geological Survey (USGS). Laboratory investigations on cores from the preshot borings were conducted by the U.S. Army Engineer Waterways Experiment Station (WES) under the sponsorship of the U.S. Atomic Energy Commission (AEC).

Postshot field and laboratory investigations were conducted by WES under the sponsorship of the U.S. Army Engineer Nuclear Cratering Group (NCG). The Lawrence Livermore Laboratory (LLL) also conducted postshot investigations on the DANNY BOY crater.

The rock media at the DANNY BOY site consist of a moderately fractured basalt of Pleistocene or Pliocene age that caps a relatively thick sequence of soft tuffs and tuffaceous alluvium. The basalt cap varies from 204 to 229 ft in thickness and is composed of at least two separate flows. The upper flow, consisting of a vesicular zone overlying a nonvesicular zone, is relatively constant in overall thickness throughout the mesa, varying from 140 to 160 ft. The lower flow, averaging 68 ft in thickness, is more variable in lithologic composition, encompassing possibly two individual flow units. No borehole camera photographs were made of the preshot holes, and therefore little detailed information is known concerning the preshot structural conditions at the DANNY BOY site. Laboratory tests indicated that the properties of the basalt vary widely, depending on the vesicularity of the basalt. The unconfined compressive strength generally increases as the density of the basalt increases.

Postshot investigations indicated that the uplift of the ground surface at the crater perimeter varied from 8.5 to 20.2 ft, and averaged 14.5 ft. No indication of faulting or overturning was noted in trenches excavated through the ejecta. The average preshot joint spacing based on measurements of natural joints and postshot vertical borings varied between 1.25 and 1.6 ft. The blast-induced fractures developed in a subparallel or parallel fashion to the preshot joint system. The structure pattern at the site remained essentially unchanged after the blast, except for an increase in the total number of fractures present and a slight increase in the overall variability of the joint pattern. In general, the natural joints tended to open up as a result of the blast.

The DANNY BOY crater is too small in relation to the characteristics of the material cratered to provide much insight into crater stability. All components of the slope are relatively stable, and slope readjustments, while probable, should be both slow and surficial.

PNE 5006 June 1966

TRACE ELEMENTS IN COMMON ROCK TYPES AND THEIR RELATIVE IMPORTANCE IN NEUTRON-INDUCED RADIOACTIVITY CALCULATIONS

Paul, R.A. and Day, W.C.

The chemical composition of the rock surrounding an underground nuclear detonation must be known or assumed when calculations of the resulting neutron-induced radioactivity are attempted. A typical chemical analysis of rock samples does not include certain trace elements which have high neutron-capture cross sections. A literature search was undertaken to determine the average and range of content of these trace elements in common rock types to permit an evaluation of their relative importance in neutron-induced radioactivity calculations.

The elements considered in the study were Dy, Gd, Eu, Sm, Nd, Cd, Ag, Co, Cr, V, Sc, Cl, S, B, and Li. Data are reported giving content of these elements in ten igneous rock types and three sedimentary rock types. The five elements Gd, Eu, Sm, B, and Cl were found to occur in most rock types in quantities which would significantly affect neutron-induced radioactivity calculations.

Calculations of induced radioactivity were performed for granite using maximum, average, and minimum trace element values obtained from the literature search. Calculations were also performed using average trace element values for four other igneous rocks and two sedimentary rocks. It is concluded that, in general, use of the average values for trace elements presented in this report is adequate for assessing the production quantities of radionuclides induced external to the device for use in feasibility studies for large scale excavation projects and other underground nuclear detonations when detailed chemical analyses of emplacement media are not available.

PNE 5008 February 1969

DISTRIBUTION OF SELECTED TRACE ELEMENTS IN ROCKS

Kley, R. J.

This report discusses factors influencing trace element distribution in rocks, tabulates maximum and minimum concentrations of twenty-nine trace elements in various common rock types, and briefly describes the geochemical behavior of each of these elements. A procedure is outlined for predicting concentrations of these selected elements in various rock types.

On the basis of this study it is concluded that:

1. Trace element concentration varies systematically according to the gross mineralogical composition of the host rock.

2. Mineralogical composition of the host rock is the primary determinant of trace element concentrations.

3. Knowledge of rock mineralogy as provided by conventional petrographic analyses serves as a basis for estimating trace element concentrations.

PNE 5009 August 1967

ENGINEERING PROPERTIES OF NUCLEAR CRATERS: REPORT 4, THE FORMATION AND INITIAL STABILITY OF SLOPES ON COHESIONLESS MATERIALS

MacIver, B. N.

The purpose of the study of engineering properties of nuclear craters is to identify and describe the physical properties that will control the use of a nuclear crater for engineering purposes. One of the prime considerations in the engineering use of a nuclear crater is the stability of the crater slopes. The late time mechanism of explosion crater formation is a deposition phenomenon.

The inclination of a slope formed by deposition of cohesionless material is termed the angle of deposition. The angle of repose is defined in this report as the maximum possible inclination of a slope of cohesionless material. This definition differs from some common definitions of angle of repose. The factor of safety of a slope formed by deposition is defined as the ratio of the tangent of the angle of repose to the tangent of the angle of deposition. Variations are recognized in the angle of deposition with the manner of deposition, and in the angle of repose with varying relative density and particle orientation.

Such factors as particle size, shape, and angularity, structure of particle aggregations, manner of deposition, and geometry of slopes are discussed with regard to their relative influence on each of the aforementioned angles. A few simple analytical relations are given to aid in understanding the behavior of particles during deposition and their stability on an inclined surface. Empirical data from laboratory tests, stockpiles, rock-fill dams, natural slopes, explosion-produced craters, etc., are presented and compared.

It is concluded that angles of deposition for cohesionless rock and soil materials vary between 22 and 42 deg, and generally lie between 34 and 37 deg for angular particles, whereas angles of repose range between 27 and 47 deg, and generally lie between 37 and 47 deg for angular particles. The initial factor of safety of a slope formed by deposition will probably exceed 1.1 but will be no more than 1.5 in most cases.

PNE 5010 September 1967

ENGINEERING PROPERTIES OF NUCLEAR CRATERS: A STUDY OF SELECTED ROCK EXCAVATIONS AS RELATED TO LARGE NUCLEAR CRATERS

Kley, R. J. and Lutton, R. J.

Analogies between nuclear and conventional excavations are developed from a tabulation of data from 153 mine, quarry, roadway, and dam excavations. The following

factors were used as the basis for tabulation of conventional excavation data: purpose, location, precipitation, temperature, ground water level, lithology, mass strength, structural pattern, slope plan, slope profile, depth of excavation, slope height, average inclination, and stability.

It was found that average slope inclination tends to be greatest for hard material and for material lacking a well-developed structure, and that inclination tends to decrease with increasing slope height for excavated slopes reported to be stable.

The authors conclude that good analogies are to be found in shape, slope height, depth of excavation, and slope inclination. Loadings of waste material at the rim of some open pit mines may be analogous to ejecta on the lips of nuclear craters. Rubble zones found in some open pit mines may be analogous to the fallback zones of nuclear craters. Differences between preshot and postshot characteristics of cratered media must be appreciated in evaluating analogies between features of conventional excavations and preshot features of nuclear excavation sites.

Brief descriptions of 21 selected excavations are presented in Appendix A. The results of this study serve as an aid to judgment of nuclear crater slope stability. Potential subjects for further study are identified.

PNE 5011 September 1967

THE FORMATION OF A CRATER AS OBSERVED IN A SERIES OF LABORATORY-SCALE CRATERING EXPERIMENTS

Bening, R. G.

A qualitative description of the formation of a crater is developed on the basis of a series of laboratory-scale cratering experiments. The results of 41 1-lb single-charge cratering detonations in a concrete sand placed under controlled conditions are summarized. The effect of depth of burst on crater dimensions is illustrated. The crater formed by a one-pound charge buried at a depth of burst of 2 ft is selected for analysis because the ratio of depth of burst to depth of apparent crater is similar to that considered desirable for a prototype nuclear excavation. On the basis of these experiments and a series of gram-size, half-space cratering experiments conducted behind a Plexiglas plate, a description of the formation of a crater is hypothesized. Subsidence or slumping of the cavity walls during the formation of the crater is shown to play an important part in the formational process. The importance of this mechanism to the analysis of crater stability is discussed.

PNE 5012-I February 1968

ENGINEERING PROPERTIES OF CRATERS: DESCRIPTION OF CRATER ZONES AND SITE INVESTIGATION METHODS—REPORT I

Fisher, P. R.

This report discusses: (1) the current state of knowledge concerning the physical character of the distinct zones of disturbance surrounding a nuclear or high explosive crater, (2) the scope and techniques of engineering properties investigations at the sites of cratering experiments, and (3) methods for predicting the character of crater zones from the results of predetonation investigations. Information contained in this report is based on data obtained from craters produced in dry materials.

The distinct zones of disturbance observed at nuclear and high explosive craters are the fallback zone, the ejecta zone, and the rupture zone (which includes the zone of upthrust).

The fallback zone is bounded by the apparent and true craters. In dry, slightly cohesive desert alluvium, the physical characteristics of the fallback are similar to those of the in situ materials. In dry rock, the fallback has distinctly different characteristics than the in situ materials; a loose mass of rock fragments with a bulk density of from 60 to 75% of the in situ bulk density is produced.

The ejecta zone is bounded by the apparent and true crater lip surfaces and, in its upper portion, exhibits very similar physical characteristics to that of the fallback. The lower portion of the ejecta usually consists of folded-over materials with physical characteristics similar to the underlying rupture-zone materials.

The rupture zone extends outward from the true crater boundary. It is characterized by shearing, displacements, fracturing, and changes in material bulk density. In dry desert alluvium, compaction occurs adjacent to the true crater boundary, and the development of observed open fractures is minimal. In dry rock, significant increases in fracture frequency and "effective porosity," with attendant decreases in bulk density, are observed in the rupture zone.

The following characteristics for craters in dry materials may be predicted with reasonable accuracy: (1) size and shape of the apparent crater, (2) size and shape of the true crater, (3) shape and extent of the rupture zone, (4) particle size distribution and bulking factor of the fallback and ejecta, (5) orientation of blast fractures, (6) relative intensity of blast fracturing, and (7) detonation-induced increases in effective porosity with accompanying changes in rupture zone bulk density.

Site investigations serve three purposes: (1) selection of the site for a cratering experiment, (2) detailed preshot documentation of the in situ physical characteristics of the site media, and (3) detailed postshot documentation of the physical characteristics of the crater zones.

Site-selection investigations are designed to insure that the site selected meets the established experimental criteria. The site-documentation investigations are designed so that comparisons can be made between the preshot in situ characteristics of

the medium and the postshot character of the crater zones. The information obtained as a result of these comparisons serves as the basis for predicting the character and extent of crater zones at subsequent cratering experiments. New and better methods for site investigation and crater prediction develop as the results of earlier studies are analyzed.

PNE 5013 March 1971

CRATER STABILITY UNDER THE INFLUENCE OF LARGE SEISMIC MOTIONS

Shackelford, T. J.

This report is an empirical study of the effects of large seismic motions on crater slopes. Data were obtained from measurements of the effects of the seismic motions generated by the HANDLEY Event on the CABRIOLET and SCHOONER craters. Accelerometers recorded the ground motions; aerial photographs and ground surveys documented the permanent ground displacements.

The HANDLEY Event was detonated on Pahute Mesa at the Nevada Test Site approximately 10,000 ft from the CABRIOLET crater and 18,000 ft from the SCHOONER crater. The slopes at CABRIOLET were subjected to the estimated peak radial (horizontal) acceleration of 0.74 g; the slopes at SCHOONER, to 0.36 g.

Material displacements at CABRIOLET and SCHOONER craters were confined to the loose surface material and individual boulders. Visible downslope movement occurred in the fallback, and tension cracks appeared in the apparent crater lips, but no adjustments in the true crater were observed. Since no major changes in crater geometry occurred under severe ground acceleration, it appears that crater slopes are likely to remain essentially stable when subjected to large seismic motions.

F. Miscellaneous Report Abstracts

This section consists of all reports sponsored by EERL/NCG that do not fall into the previous categories. The majority of these are WES reports, which were written at the Waterways Experiment Station, Vicksburg, Mississippi; others are reports prepared at various universities.

EERC 69-16 December 1969

THE BEHAVIOR OF SANDS UNDER SEISMIC LOADING CONDITIONS

Silver, M. L. and Seed, A. B.

Sponsored by: NCG

The volume change characteristics and the dynamic stress-strain properties of dry sand subjected to cyclic shear strains have been investigated and used to check the

applicability of a simple method for predicting the vertical settlements due to compaction in layers of dry cohesionless soils subjected to seismic loading conditions.

Dynamic testing of a medium quartz sand, performed by repeated load simple shear equipment, indicated that the shear modulus increased slightly with increasing numbers of cycles and with increasing relative density and decreases significantly with increasing values of shear strain amplitude. Modulus values determined near the upper limit of shear strain amplitude that might be expected to be induced by seismic shaking (0.1%) were as much as 40% lower than modulus values obtained at the lowest values of shear strain that were investigated (0.01%). Using a relationship between shear modulus (G) and vertical stress (σ_v) represented by a straight line on a log-log plot having the equation $G = K_m \sigma_v^m$, it was found that values of the exponent m may range between 0.5 and 0.7 depending on the shear strain amplitude.

Values of hysteretic damping determined from hysteresis loops showed that damping increased with increasing shear strain amplitude and decreased slightly with increasing numbers of cycles and increasing values of vertical stress. The relationship between damping and shear strain was essentially independent of the relative density of the sand.

Measurements of the volume change behavior of sands under cyclic loading simple shear conditions suggest that the vertical strain due to compaction is not significantly affected by values of vertical stress and depends only on the shear strain amplitude induced in the sample at shear strains exceeding 0.05%. This indicates that cyclic shear strain, which deforms the sample allowing particles to move into denser packing, may well be a fundamental parameter in determining the volume change behavior of cohesionless soil under dynamic loading conditions. On the other hand, as the vertical stress increases, the cyclic shear stress necessary to cause any degree of compaction also increases, a result in agreement with studies of the liquefaction potential of sands subjected to cyclic loading.

A method for calculating the settlements of sand layers subjected to horizontal accelerations is suggested together with details of a typical analysis. For a variety of test conditions, calculated settlements agree reasonably well with measured settlements of 1-ft high layers of sand subjected to horizontal shaking in shaking table tests. Thus it seems reasonable to believe that the proposed technique might be used as a first approximation for estimating the volume change tendencies and ground surface settlements induced in deposits of cohesionless soil caused by seismic shaking.

WES MP H-69-5 May 1969

HYDRAULIC CHARACTERISTICS OF NUCLEAR EXCAVATED CHANNELS

Sager, R. A., McNair, E. C., Jr., and Keulegan, G. H.

Sponsored by: NCG

This study was conducted primarily to obtain a method of determining Manning's n that could be used to approximate the discharge through channels formed by a selected range of applications of nuclear explosives. The study included tests of three small scale channel sections, one channel with straight smooth sides, and two channels with selected forms of expanding and contracting sections throughout the length of each channel. Concurrently an analysis of isostatic losses was conducted to allow the development of a general equation for predicting an effective Manning's n that could be used for channels with significant expansions and contractions. An equation applicable to the specific range of expansions and contractions subjected to model tests is developed, using the results of the hydraulic model tests.

General information on velocity distribution within the channels is presented. The data showed that flow separation occurs at each significant area of contraction with resulting modification of the flow distribution downstream from the expanding area.

WES MP H-69-6 May 1969

CANAL DENSITY CURRENTS

Sager, R. A.

Sponsored by: NCG

Three tests were conducted to provide basic data showing the effects of density currents for each of the three conditions in a sea-level canal connecting two seas and intercepting a channel carrying freshwater. Two cross-sectional areas of the canal were tested, 60,000 ft^2 and 300,000 ft^2, with tidal ranges in one sea of 10.7 and 22 ft tested for the 60,000-ft^2 channel and 10.7 ft tidal range for the 300,000 ft^2 channel. The second basin in each test was held at a constant water-surface level throughout each test. The total length of the canal for each test was 260,000 ft. Hydrographs with an excess of 60,000 ft^3/sec peak discharge were assumed for each test.

Results of the tests indicate that significant density current can be expected in the 60,000-ft^2 channel, whereas density current effects in the 30,000-ft^2 channel were confined to a relatively few tidal cycles and were of much less significance than the currents experienced with the 60,000-ft^2 channel.

WES MP S-68-3 May 1968

APPLICATION OF FINITE ELEMENT METHOD IN DETERMINING STABILITY OF CRATER SLOPES (PRELIMINARY REPORT)

Banks, D. C. and Palmerton, J. B.

A finite element computer program for determining the stress distribution in an elastic material was applied to (a) the Boussinesq line force problem, and (b) a typical nuclear crater. These analyses were performed to explore the potential usefulness of the finite element method for studying the stability of slopes excavated by nuclear explosions.

Included also is a brief description of the theory of the finite element method. The limitations of the codes now available to the Waterways Experiment Station are discussed, and suggestions are made for improving them to meet specific requirements for analyzing crater slope stability.

WES MP S-68-8 July 1968

SELECTED METHODS FOR ANALYZING THE STABILITY OF CRATER SLOPES

Banks, D. C.

Sponsored by: NCG

The results of a study to select methods for analyzing the stability of crater slopes are presented in this report. Information is given on the nature of input required, such as crater geometry, unit weights, shear strength, and seepage pressures. The selected methods are discussed in detail, and examples of their application are presented.

The report does not describe all methods which are found in literature, although these were reviewed during the study. The three selected methods presented are: (a) the Bishop method of slices for circular slip surfaces; (b) the extension of Bishop's method to composite failure surfaces as proposed by Janbu and Nonveiller, and (c) the Seed and Sultan method of wedges. These methods were selected as representative of the best available limiting equilibrium procedures.

WES MP S-69-12 April 1969

VARIATION IN ANGLE OF INTERNAL FRICTION WITH CONFINING PRESSURE

Banks, D. C. and MacIver, B. N.

Sponsored by: NCG

This report summarizes published results of triaxial compression tests on cohesionless materials at high confining pressures. The data presented herein indicate a curved strength envelope, resulting in a decrease in angle of internal friction with

increase in normal stress. An analysis of the data is made and a function relation is presented for the ϕ_o angle (angle of maximum stress obliquity) in terms of normal stress on the failure plane.

The significance of a curved strength envelope is investigated for the stability of infinite, simple finite, and crater slopes composed of dry cohesionless material. Preliminary analyses, for the case of a partially submerged crater slope are also presented. The analyses indicate that a deep failure surface may be more critical than a shallow surface when the phenomenon of a curved strength envelope is considered.

Empirical stable slope data abstracted from a letter concerning canal excavation by nuclear cratering are presented in Appendix A.

WES MP S72-2 January 1972

APPLICATION OF FINITE ELEMENT METHOD IN DETERMINING STABILITY OF CRATER SLOPES

Palmerton, J. B. and Banks, D. C.

The investigations reported comprise studies to evaluate applicability of the finite element method to stability analysis of explosively excavated slopes.

A finite element program based on nonlinear material properties was developed during this study. The program incorporates a capability to simulate incremental construction of slopes of arbitrary geometry either by excavation or by building up. The stress-strain relationships of materials forming the slope and its foundations are approximated by hyperbolic curves. The hyperbolic curves are asymptotic to the yield strength of the materials as defined by Mohr-Coulomb strength parameters, c (cohesion) and ϕ (friction angle). Initial states of stress may be incorporated into the analyses.

Several examples of simple slopes under various initial states of stress were analyzed. Additional examples were a symmetrical, homogeneous embankment on a rigid foundation and hypothetical row crater excavation slope. Stresses and displacements for the different examples are presented along with a method for determining the factor of safety of a slope from nonlinear stress analysis.

WES MP 3-895 May 1967

PRESHOT GEOLOGICAL AND ENGINEERING CONDITIONS AT THE PROJECT FLIVVER SITE, NEVADA TEST SITE

Carter, L. D., Bailey, D. M., and Hunt, R. W.

Sponsored by: NCG

The site of the FLIVVER experiment is in basalt on the central ridge of Buckboard Mesa, Nevada Test Site. A soil layer averaging 2-ft thick covers the site.

The basalt, which is about 237-ft thick at the FLIVVER site, can be divided into three units: (1) an upper, vesicular unit; (2) a middle, dense unit; and (3) a thin, basalt vesicular unit.

Deformation of vesicles and concentration of vesicles into layers during viscous flowage have imparted a pronounced layering to the basalt. The orientation of these

layers indicates that the major structure of the lava is cylindrical. Minor folding in the upper portion of the flow complicates this structure. The trend of the ridge and the attitudes of flow layers indicate that the flow curved eastward as it flowed south-southeast across the site.

The frequency of joints decreases downward to a minimum at a depth between 40 and 80 ft. Between 80 and 160 ft there is a slight overall increase in joint frequency, with a prominent increase occurring at roughly 160 ft. Joint spacing ranges from less than 0.1 to greater than 20 ft.

Results are presented on laboratory determinations of specific gravity of solids, dry bulk densities, porosities, tensile splitting strengths, unconfined compressive strengths, triaxial compressive strengths, static and dynamic moduli of elasticity, static and dynamic Poisson's ratios, and compression wave velocities. Mohr's failure envelopes were constructed based on data from tensile splitting tests, unconfined compression tests, and triaxial compression tests.

WES MP 3-902 June 1967

CHUKAR MESA INVESTIGATION: EXPLORATION OF AREAS FOR A POSSIBLE HARD-ROCK CRATERING SITE—BUGGY I

Lutton, R. J. and Hunt, R. W.

Sponsored by: NCG

A site in dry basalt was selected from six possible areas at the Nevada Test Site for a low-yield nuclear row-charge cratering experiment. Topography is relatively flat over an approximately square area about 3,000 ft across; the area is bounded on three sides by canyons. The site consists of about 330 ft of horizontal basalt flows resting on tuff breccia, other basalt flows, and thick vitrophyric flow.

Unconfined compressive strengths on intact materials tend to decrease with increasing porosity from 23,000 lb/in.^{2} for dense basalt to 6,200 lb/in.^{2} for vesicular basalt with 20 to 30% vesicles. The porous tuff breccia has compressive strengths as low as 1,100 lb/in.^{2}. The basalt is moderately to highly jointed.

WES MP 3-974 February 1968

SETTLEMENT OF FALLBACK MATERIALS

Sherman, W. C.

Sponsored by: NCG

To provide a means for predicting the ultimate settlements of cohesionless fallback materials and to determine the nature of such settlements, a review was made of published data on laboratory investigations of crushed rock compressibility and field settlement data of rock fill dams.

The available data indicate that the fallback materials resulting from the formation of nuclear craters in rock will be subject to a continuing time-dependent settlement

after deposition. The settlements should continue at a decreasing rate with time except that a marked increase in settlement can be expected when saturation occurs. As nuclear craters will be subjected to seismic forces during their design lives, additional settlements due to dynamic loadings can be expected. A review of the performance of rock-fill dams subjected to earthquakes indicates that rock-fill dams are basically very resistant to earthquakes. However, the data on seismic behavior of rock-fill dams are meager, and it is considered that more research is needed before any firm conclusions can be drawn.

WES MP 3-981 March 1968
SURVEY OF SLOPE FAILURES IN RESERVOIRS
Sherman, W. C.
Sponsored by: NCG

The U. S. Army Engineer Waterways Experiment Station (WES) is conducting a program of studies at the request of the U. S. Army Engineer Nuclear Cratering Group (NCG) to develop analytical and empirical methods for evaluating the stability of nuclear craters. In order to determine the effects of initial submergence on the stability of the cohesionless fallback materials, a survey was made of various Corps of Engineers offices concerning performance of reservoir slopes during initial submergence. This report describes the results of that survey.

WES TE-72-2 April 1972
SEEPAGE AND GROUNDWATER EFFECTS ASSOCIATED WITH EXPLOSIVE CRATERING
Duncan, J. M., Witherspoon, P. A., Mitchell, J. K., Watkins, D. J., Hardcastle, J. H., and Chen, J. C.

This report presents the results of a study of the groundwater and seepage conditions likely to be produced in the vicinity of explosively formed row craters. The limitations of indirect methods for the determination of the permeability of fallback and rupture zones are evaluated. Analyses of a range of possible groundwater conditions modeled by the finite element method are presented. The shear strength characteristics of fallback and rupture zone materials are briefly considered. The influence of seepage on the stability of crater slopes is discussed.

The study indicates that the finite element method is an effective tool for the study of groundwater conditions in the vicinity of craters. Reliable values of permeability of the rupture zone material are required if accurate results are to be obtained. Reasonable estimates of fallback and ejecta permeabilities may be possible if particle size distributions are known which include the smallest sizes.

Excluding situations in which peculiar boundary conditions are imposed by the site geology, it is unlikely that seepage has a major influence on the stability of crater

slopes in hard rock such as basalt. In soft rocks in which the permeability of fallback material is reduced by weathering, slope instability resulting from excessively large seepage forces can be expected to pose major problems.

WES TR 3-699—Report 1 October 1965

SITE SELECTION INVESTIGATIONS, WET MEDIUM CRATERING EXPERIMENTS

Saucier, R. T. and Banks, D. C.

Sponsored by: NCG

Investigations described in this report were conducted to select a site suitable for producing craters in a saturated cohesive medium by small-scale high-energy detonations. According to prescribed criteria, the ideal site would be a large (200 acres or more), cleared, moderately flat tract of Federally-owned land characterized by soft, homogeneous clays to a minimum depth of 40 ft.

An evaluation of the U. S. by physical divisions revealed that suitable sites might occur in four general areas; i.e., (1) the Lake Bonneville area, (2) the Lake Agassiz area, (3) the Great Lakes area, and (4) the Lower Mississippi Valley area. Acquisition and analyses of pertinent data on these areas indicated a need for field reconnaissances except in the case of the Great Lakes area which was eliminated from further consideration because of heterogeneous soil deposits.

A reconnaissance of the Lake Bonneville area indicated the presence of apparently favorable test site conditions in a portion of the Dugway Proving Ground, Utah, while a reconnaissance of the Lake Agassiz area of North Dakota and Minnesota revealed generally unfavorable soil conditions. In regard to the Lower Mississippi Valley area, three possible site areas were visited: one situated on backswamp deposits and two situated on abandoned channel deposits. Of the three, the Brickeys site (abandoned channel deposits) in eastern Arkansas was considered to be potentially the most favorable.

Three borings were made at the Dugway Proving Ground site and two borings at the Brickey site to investigate the depth and homogeneity of the clay deposits. Natural water contents and unconfined compressive strengths were determined on selected undisturbed samples from both sites.

Although stratified, the clays at the Dugway Proving Ground site are of sufficient thickness and homogeneity for conduct of the cratering experiments. Water contents (about 45%) and the position of the water table (about 3.5 ft below ground surface) are within the desired ranges while the shear strengths are slightly higher than desired (500 to 1,400 lb/ft^2 versus a desired range of 400 to 800 lb/ft^2). At the Brickeys site the clays were found to have comparable water contents and lower shear strengths (200 to 500 lb/ft^2) but are generally less satisfactory than at the Dugway Proving Ground site because of doubtful thickness (prove thickness only 36.5 ft) and scattered sand lenses and organic fragments.

Considering the soil conditions together with such factors as land ownership, proximity of cultural features, and probability of surface flooding, it is concluded that the Dugway Proving Ground site is more suitable for the conduct of the project than any other site considered.

WES TR 3-699—Report 2 October 1965

THEORETICAL STUDIES OF CRATERING MECHANISMS AFFECTING THE STABILITY OF CRATERED SLOPES, PHASE II

Vesic, A. S., Wilson, W. E., Clough, G. W., and Tai, Tein-Lie

Sponsored by: NCG

In this second phase of the research project on mechanism of cratering and stability of cratered slopes, additional contributions to the knowledge of cratering phenomena were made.

Solutions for a charge exploding in a compressible medium indicate pronounced effects of volume changes in the plastic zones surrounding the expanding cavity. It is shown that these effects can be taken into account by reducing the rigidity index of the medium in question. Suggestions are given for experimental determination of the average volumetric strain Δ of the plastic zone that figures in computations of this kind.

General solutions developed for deep craters indicate that the critical depth of burst, at which the overburden is sheared off by the expanding gases in the cavity, depends on soil compressibility and volume change (as reflected in the reduced rigidity index I_{rr}), angle of shearing resistance Φ, as well as on the ratio of cohesion (shear intercept) c to the overburden pressure γ_z. Thus, the critical depths of burst cannot be scaled directly by following a cube-root or any other semiempirical scaling law.

Numerous additional comparisons of computed and measured true crater dimensions indicate good agreement of field observations with the theory of cratering developed in the first report. At the same time, small-scale experiments and high speed movie records of cratering phenomena observed through a transparent wall substantiate the basic assumptions on which the new theory was based as well as its consequences, as evidenced by shapes and sizes of actual craters formed.

WES TR 3-699—Report 3 August 1965

REVIEW AND ANALYSIS OF AVAILABLE INFORMATION ON SLOPES EXCAVATED IN WEAK SHALES

Hirschfeld, R. C., Whitman, R. V., and Wolfskill, L. A.

Sponsored by: NCG

This report is concerned with the slope stability problems which will arise if a new canal is to be excavated through the types of weak shale encountered along the present Panama Canal. The main body of the report is divided into three parts: (a) a

discussion of the need for slope stability analyses for new routes, and of the approaches which might be used to obtain the necessary data; (b) a review of past experience concerning slopes in the field and concerning laboratory tests, especially the experience from the present Panama Canal; and (c) a description of some new studies, including some first attempts at a reanalysis of the landslide experience at the Panama Canal and including the development of new laboratory test equipment.

WES TR 3-699—Report 5 December 1966
RESIDUAL SHEAR STRENGTH OF WEAK SHALES
Herrman, H. G. and Wolfskill, L. A.
Sponsored by: NCG

This report is concerned with the laboratory determination of the residual shear strength of weak shales such as might be encountered in construction within the Canal Zone. This laboratory measurement is proposed mainly as an index property to estimate the potential for shales or deeply weathered rocks to lose substantial strength with time. In addition to the residual strength parameter, five other index properties are outlined to form a comprehensive means for expediently evaluating potential loss of strength.

By definition, the residual shear strength is a constant for any given soil regardless of stress history, and is the lowest "ultimate" strength. In practice, however, the laboratory measurements of residual strength can vary simply because of failure to reach this lowest strength. The main effort in this present research is to develop the equipment and testing procedures to reliably measure residual strength. It was found that the repeated direct shear test, with about 30 repetitions of loading on mechanically disintegrated and resedimented samples, resulted in an adequate index property test. The results of comprehensive testing of two Canal Zone shales (from the Cucaracha and the Culebra formations). Pierre shale from the Oahe damsite in South Dakota and a kaolinite clay are contained in the report.

WES TR 3-699—Report 6 March 1967
THEORETICAL STUDIES OF CRATERING MECHANISMS AFFECTING THE STABILITY OF CRATERED SLOPES, PHASE III
Vesic, A. S., Boutwell, G. P., Jr., and Tai, Tein-Lie
Sponsored by: NCG

The present, third phase of this project is devoted to study of cratering phenomena in three specific situations that are of particular interest in engineering practice, namely: (1) the situation where the cratered medium is submerged under the water table; (2) the situation where the surface of the cratered medium is sloped; and (3) the situation where several explosive charges are set off simultaneously in a medium.

In particular, Chapter I of this report is devoted to the experimental study of cratering phenomena in saturated or submerged media. Chapter II describes the experiments in which pore-fluid stress waves caused by an explosion in a mass of submerged, dense sand were measured and discussed, with particular emphasis on possible residual pore-fluid stresses. Chapter III is devoted to the problem of craters formed by explosions close to the sloped surface of a semi-infinite medium. Chapter IV deals with cratering phenomena caused by multiple charges, where coalescence of cavities may occur following detonation.

G. Article Abstracts

This section consists of articles published by members of EERL/NCG in various periodicals. Short summaries of the articles are arranged in a numbered sequence relative to their date of publication.

Article 1

TRACE ELEMENTS IN COMMON ROCK TYPES AND THEIR RELATIVE IMPORTANCE IN NEUTRON-INDUCED RADIOACTIVITY CALCULATIONS

Day, W.C. and Paul, R.A.

Health Physics—Pergamon Press, 1968, Vol 14, pp 311-329

The chemical composition of the rock surrounding an underground nuclear detonation must be known or assumed when calculations of the resulting neutron-induced radioactivity are attempted. A typical chemical analysis of rock samples does not include certain trace elements which have high neutron-capture cross sections. A literature search was undertaken to determine the average and range of content of these trace elements in common rock types to permit an evaluation of their relative importance in neutron-induced radioactivity calculations.

The elements considered in the study were Dy, Gd, Eu, Sm, Nd, Cd, Ag, Co, Gr, V, Sc, Cl, S, B, and Li. Data are reported giving content of these elements in ten igneous rock types and three sedimentary rock types. The five elements Gd, Eu, Sm, B, and Cl were found to occur in most rock types in quantities which would significantly affect neutron-induced radioactivity calculations.

Calculations of induced radioactivity were performed for granite using maximum, average, and minimum trace element values obtained from the literature search. Calculations were also performed using average trace element values for four other igneous rocks and three sedimentary rocks. It is concluded that, in general, use of the average values for trace elements presented in this report is adequate for assessing the production quantities of radionuclides induced external to the device for use in feasibility studies for large scale excavation projects and other underground nuclear detonations when detailed chemical analyses of emplacement media are not available.

Article 2

NUCLEAR EXCAVATION DESIGN OF A TRANSISTHMIAN SEA-LEVEL CANAL

Hughes, B.C.

Nuclear Applications and Technology—Vol 7, September 1969

This paper presents an up-to-date analysis of the application of nuclear excavation technology to the design of a sea-level canal connecting the Atlantic and Pacific Oceans. This analysis is based on the technical data obtained to date under the auspices of the Atlantic-Pacific Interoceanic Canal Study Commission. Consideration is given in this paper to use of nuclear methods in the construction of a sea-level canal through the Darien region of Panama (Route 17) and the Atrato-Truando region of northwest Colombia (Route 25).

The site data required for a comprehensive nuclear excavation design analysis of a proposed sea-level alignment include information pertaining to site topography, geology, hydrography, hydrology, meteorology, seismic propagation characteristics, bio-environmental conditions, and medico-ecology. These data are being used, together with data pertaining to nuclear explosive characteristics, cratering characteristics of pertinent geologic media, nuclear cratering detonation effects and channel design criteria, to develop an engineering-safety-cost analysis which is the basis for the nuclear excavation design.

The results of geologic investigations to date along the 46-mi Route 17 alignment indicate that approximately 20 mi of the alignment through the Chucunaque Valley encounters a weak saturated clay shale while the balance of the excavation would be through relatively competent rock. In view of the unfavorable long-term slope stability characteristics of these shales, techniques were developed for using nuclear explosives to produce linear craters that have initially flat slopes of the order of 7 to 9 deg. Experiments indicate that nuclear excavation using a two-pass, triple-row array detonation system may offer a solution to this problem.

A preliminary analysis of the topography and geology along the Route 25 sea-level canal alignment through northwest Colombia indicates that conventional excavation techniques, primarily hydraulic dredging, would be the most reasonable method of excavating ~78 mi of the 100-mi alignment. The remaining 23 mi of the alignment, through the Continental Divide, would be excavated using nuclear explosives.

Studies in progress pertain to the safety aspects of using nuclear methods to construct a transisthmian sea-level canal, including consideration of seismic propagation, airblast acoustical wave phenomena, and radioactivity release. The results of such studies to date indicate that the potentially damaging effect on buildings from ground motions resulting from seismic propagations from the nuclear detonations will be the major factor in determining the maximum aggregate yield that can be detonated at any one time along the selected alignment.

Article 3

THE CORPS OF ENGINEERS NUCLEAR CONSTRUCTION RESEARCH PROGRAM

Day, W. C.

Nuclear Applications and Technology—Vol 7, September 1969

The U. S. Army Corps of Engineers Nuclear Cratering Group (NDG) program activities include: (1) cratering calibration of various geologic media and development of techniques designed to provide a desired crater geometry with chemical high-explosive detonations; (2) joint planning of and technical participation in AEC nuclear-excavation experiments; (3) development of data on the engineering properties of nuclear craters; (4) development of civil works nuclear construction technology; (5) accomplishment of engineering studies of nuclear construction feasibility; and (6) execution of joint CE/AEC civil works nuclear construction experiments.

Four conceptual nuclear-construction applications have been identified as having a significant potential for accomplishment: (1) nuclear quarrying to produce rockfill or aggregate; (2) nuclear ejecta dam construction; (3) nuclear harbor construction; and (4) nuclear canal excavation. The nuclear quarry has been identified as the most direct application of present technology. A site is currently being sought for a nuclear quarry experiment.

Article 4

FORMATION AND ENGINEERING CHARACTERISTICS OF NUCLEAR CRATERS FOR CONSTRUCTION PURPOSES

Hughes, B. C.

Army Science Conference Proceedings, 18-21 June 1968, Vol 1

This paper discusses the technology of nuclear excavation as developed to date in the joint Atomic Energy Commission/Corps of Engineers nuclear excavation research program. Detailed data are presented concerning crater formation phenomenology, engineering characteristics of nuclear craters, and potential nuclear crater construction applications. Techniques for predicting crater geometry using both computer calculations based on stress wave propagation analysis and empirical scaling laws are discussed. The various zones of disturbance surrounding a nuclear crater are identified and described and information is presented concerning the extent and physical characteristics of these zones. It is concluded that the nuclear excavation research program to date has confirmed the basic concept of crater formation phenomenology and resulted in the development of techniques for predicting, with a reasonable degree of accuracy, the geometry and engineering properties of nuclear craters. An understanding of these phenomena is required in order to assess the engineering usefulness of an explosion-produced excavation. It is anticipated that continuing advances will be made

in the state-of-the-art over the next few years and the technology will exist for using nuclear excavation techniques to accomplish a number of construction projects.

Article 5
NUCLEAR EXCAVATION RESEARCH
Kurtz, M. K., Jr.
The Military Engineer, No. 397, September-October 1968

The main emphasis in nuclear excavation research has been experimental detonation of explosive charges at various depths of burst. Charge size ranged from 0.8 g HE to many kiloton (TNT equivalent) nuclear explosions. Nuclear excavation appears feasible for canals, quarries and harbors. Primary advantage is cost compared to conventional means. Time-saving may be significant in some cases. Eighty to 90% of radioactivity is buried inside the crater when charge is at "optimum depth of burial." Ground seismic motion is a major concern. Much more empirical basis is needed for conclusions.

Article 6
THE CORPS OF ENGINEERS NUCLEAR CONSTRUCTION RESEARCH PROGRAM
Hughes, B. C.
"Education for Peaceful Uses of Nuclear Explosives"
Lynn B. Weaver, Editor, University of Arizona Press, 1970

The major Corps' effort in nuclear excavation research is performed by the Nuclear Cratering Group, LLL, Livermore, California. Crater formation from nuclear explosion is the primary research area. Empirical means for prediction of crater size are being developed. Use is envisioned in quarrying, dam building, harbor and canal construction.

Article 7
A CONCEPT OF ROW CRATER ENHANCEMENT
Redpath, B. B.
Army Science Conference Proceedings, 1970

The effect of simultaneous detonation of adjacent charges is explored. Charges aligned in a row, detonated simultaneously, yield a larger crater than the same charges detonated independently. This phenomenon is named enhancement. A quantitative analysis is developed.

Article 8

STATUS OF THE INTEROCEANIC CANAL STUDY

Groves, R. H.

Proceedings, Symposium on Engineering with Nuclear Explosives, 14-16 January 1970, Vol 1, p 780

Summing up our present situation, I would say that we have not yet attained the objectives of our study, as they pertain to nuclear excavation, nor are we likely to do so in the time remaining to us. We have not yet established the feasibility of constructing by nuclear means a sea-level interoceanic canal; we are unable to state unequivocally that were this technique feasible, it would be the best.

We know now that a conventionally constructed canal is technically feasible and we know its approximate cost. We are confident from a purely engineering standpoint that it could be built, if desired.

But we recognize that the question of its technical feasibility, even though answered favorably, will not in itself govern the decision on a new canal. Many other factors—diplomatic, military, political, sociological, economic and ecological, to name but a few—must also be considered and any one of them can influence the course of action which is finally adopted.

While a conventionally constructed canal is feasible today, we cannot be sure that it would be the best solution to the canal problem until such time as we know more about nuclear excavation technology than we now know. I would expect that the necessary knowledge can be acquired before construction of a new canal begins, if only the PLOWSHARE investigations now planned are executed.

Yet, no matter when the final decision is reached concerning the sea-level canal or what it may be, I am convinced that the case for developing nuclear excavation technology is fully capable of standing on its own merits. In its techniques are such vast potentials for applications to public works that its technology must be fully developed, regardless of how the canal question is settled. And if, by developing it, the well-being of our fellow Americans is enhanced, all the time and effort that have gone into the Engineering Feasibility Study will have been worthwhile.

Article 9

EXCAVATION RESEARCH WITH CHEMICAL EXPLOSIVES

Vandenberg, W. E. and Day, W. C.

Proceedings, Symposium on Engineering with Nuclear Explosives, 14-16 January 1970, Vol 1, p 360. Sponsored by: ANS.

The U.S. Army Engineer Nuclear Cratering Group (NCG) is located at the Lawrence Livermore Laboratory in Livermore, California. NCG was established in 1962 and assigned responsibility for technical program direction of the Corps of Engineers Nuclear Excavation Research Program. The major part of the experimental program

has been the execution of chemical explosive excavation experiments. In the past, these experiments were preliminary to planned nuclear excavation experiments. The experience gained and technology developed in accomplishing these experiments has led to an expansion of NCG's research mission. The overall research and development mission now includes the development of chemical explosive excavation technology to enable the Corps of Engineers to more economically accomplish civil works construction projects of intermediate size. The current and future chemical explosive excavation experiments conducted by NCG will be planned so as to provide data that can be used in the development of both chemical and nuclear excavation technology. In addition, whenever possible, the experiments will be conducted at the specific sites of authorized civil works construction projects and will be designed to provide a useful portion of the engineering structures planned in that project.

Currently, the emphasis in the chemical explosive excavation program is on the development of design techniques for producing specific crater geometries in a variety of media. Preliminary results of two such experiments are described in this paper; Project Pre-GONDOLA III, Phase III, reservoir connection experiment, and a safety calibration series for Project TUGBOAT, a small boat harbor excavation experiment.

Article 10

PREDICTION OF GAMMA EXPOSURE RATES IN LARGE NUCLEAR CRATERS

Tami, T. M. and Day, W. C.

Proceedings, Symposium on Engineering with Nuclear Explosives, 14-16 January 1970, Vol 2, p 1544. Sponsored by: ANS.

In many civil engineering applications of nuclear explosives there is the need to reenter the crater and lip area as soon as possible after the detonation to carry out conventional construction activities. These construction activities, however, must be delayed until the gamma dose rate, or exposure rate, in and around the crater decays to acceptable levels. To estimate the time of reentry for postdetonation construction activities, the exposure rate in the crater and lip areas must be predicted as a function of time after detonation. An accurate prediction permits a project planner to effectively schedule postdetonation activities. This article gives a method for making such a prediction.

Article 11

STABILITY OF NUCLEAR CRATER SLOPES IN ROCK

Fleming, R. W., Frandsen, A. D., and LaFrenz, R. L.

Proceedings, Symposium on Engineering with Nuclear Explosives, 14-16 January 1970, Vol 2, p 1661. Sponsored by: ANS.

Due to the limited experience in wet media, other than the relatively low-yield clay shale craters, this paper will be concerned mainly with dry materials, although some qualitative discussion of seepage effects is included. Crater geometry, the factors affecting slope stability and the methods of analysis are discussed in general. This is followed by a discussion of those aspects of a crater slope which seem to bear directly on its potential stability. For convenience, the potential stability of fallback materials and rupture zone materials are discussed separately followed by a discussion of seepage characteristics. Finally, an example of stability analysis is presented.

Article 12

A SIMPLE TECHNIQUE TO DETERMINE THE SIZE DISTRIBUTION OF NUCLEAR CRATER FALLBACK AND EJECTA

Anderson, B. D., II

Proceedings, Symposium on Engineering with Nuclear Explosives, 14-16 January 1970, Vol 2, p 1726. Sponsored by: ANS.

A sampling technique was developed by Wolman (1954). A small-scale comparative test of this technique was carried out using presized gravel. The sampling technique was reevaluated in light of the results obtained during these tests. The Delesse relation was used to develop a model that theoretically justifies the results achieved. Criteria were established for the number of samples to be taken and the area to cover in sampling. In light of the results achieved, the use of the "b" intermediate axis as a measure of size for clasts seems justified. A test of the new method was accomplished at the AEC Nevada Test Site on several craters. The results achieved during these tests are considered "satisfactory."

Article 13

USE OF NUCLEAR AND CONVENTIONAL EXPLOSIVES IN CONSTRUCTION

Vandenberg, W. E.

SAME Midwest Regional Conference, 16 October 1970, St. Paul, Minnesota

The Corps of Engineers program of research into uses of explosives for construction purposes is moving forward. For the very large projects, nuclear explosive excavation promises to provide considerable cost savings and to make possible the execution of projects for public benefit that would be prohibitively expensive with conventional

methods of excavation. For some of the more nearly standard scale projects, chemical high explosive excavation promises a lesser but still significant savings in time, money and effort.

Article 14

PROJECT PRE-GONDOLA: EXPLOSIVE EXCAVATION EXPERIMENTS IN CLAY SHALE

LaFrenz, R. L.

The Military Engineer, No. 407, March-April 1970

Project Pre-GONDOLA is the code name for a series of chemical explosive cratering experiments conducted by the Army Engineer Nuclear Cratering Group from 1966 through 1969 near Fort Peck, Montana. The purpose of the experiments was to establish the cratering characteristics of weak and saturated shale, to acquire row-charge cratering experience, and to demonstrate the feasibility of connecting a row crater to a body of water.

The cratering experience gained in clay shale and the pioneer aspect of the row-charge and connection experiments combine to make Pre-GONDOLA a milestone in the development of explosive excavation techniques. The project was planned as a modeling experiment for nuclear explosive excavation. As such, it was part of the joint Atomic Energy Commission-Corps of Engineers nuclear excavation research program. Clay shale cratering experience was desired because this is the type of soil which exists in sections of the routes being considered for an Atlantic-Pacific sea-level canal. The site was excellent for additional tests in conjunction with the mission of the Nuclear Cratering Group to develop methods of using nuclear and chemical explosive excavation for construction of large-scale civil works and military projects.

Cratering experiments conducted at the Pre-GONDOLA site are listed. The major experiments in the series were Pre-GONDOLA I, Pre-GONDOLA II, and Pre-GONDOLA III Phases I, II, and III. A number of smaller experiments were made to obtain data on cratering characteristics of the material in preparation for the larger shots and to study the effect of depth of burial, explosive type, methods of stemming, charge spacing, and array configuration on the size of craters produced.

ARTICLE 15

THE CORPS OF ENGINEERS NUCLEAR CONSTRUCTION RESEARCH ACTIVITIES

Day, W. C.

For: Highway Research Board Annual Meeting, January 12-16, 1970

The U. S. Army Corps of Engineers Nuclear Cratering Group (NCG) program activities include: (1) cratering calibration of various geologic media and development

of techniques designed to provide a desired crater geometry with chemical explosive detonations; (2) joint planning of and technical participation in AEC nuclear excavation experiments; (3) development of data on the engineering properties of nuclear craters; (4) development of civil works chemical and nuclear explosive construction technology; (5) accomplishment of engineering studies of nuclear construction feasibility; and (6) execution of CE/AEC civil works nuclear construction experiments.

NCG has executed seven major chemical explosives cratering experiments. They are Pre-BUGGY I, Pre-SCHOONER I, Pre-SCHOONER II, Pre-GONDOLA I, Pre-GONDOLA II, and Pre-GONDOLA III, and Phase I of Project TUGBOAT. These experiments have provided a cratering calibration of a dry alluvium, a dry basalt, a rhyolite, and a water-saturated clay shale. Recently completed was the Pre-GONDOLA III reservoir connection experiment at Fort Peck, Montana, and the cratering and safety calibration detonations for Project TUGBOAT, a small boat harbor excavation experiment in Kawaihae Bay, Hawaii, Hawaii. The reservoir connection experiment connected a linear channel, created by two previous connecting row-charge detonations, with the Fort Peck reservoir. This linear channel connection resulted from the simultaneous detonation of five charges ranging in yield from 5 to 35 tons chemical explosive per charge. The total yield of the detonation was 70 tons. There were five Project TUGBOAT calibration detonations; four 1-ton and one 10-ton. The cratering curves and safety program results were used to design the entrance channel and berthing basin detonations scheduled for later this year.

Nuclear crater engineering properties field investigations have recently been completed for the CABRIOLET crater. A trench was excavated through the lip of the crater and the material screened and weighed. The measured bulk density of the ejecta was 124 lb/ft^3 giving a bulking factor of 1.10. Investigations are planned for some of the more recently executed nuclear cratering experiments.

Estimates of true crater volume and radiation logs in drill holes on Projects SEDAN and DANNY BOY have been used as a basis for development of a technique for predicting the expected exposure dose rates in nuclear craters. It is predicted that entry to a megaton yield crater can be made with proper rad-safe control approximately three weeks following the detonation.

Four conceptual nuclear construction applications have been identified as having significant potential for accomplishment: (1) nuclear quarrying to produce rockfill or aggregate; (2) nuclear harbor construction; (3) nuclear ejecta dam construction; and (4) nuclear canal or roadbed cut excavation. The nuclear quarry has been identified as the most direct application of present technology. The large nuclear harbor at a remote site is one of the most attractive prospects for nuclear excavation.

Article 16

A DEMONSTRATION PROJECT IN THE EXPLOSIVE EXCAVATION OF A RAILROAD CUT

Gardner, C. E.

A paper prepared for: The Ninth Annual Symposium on Engineering Geology and Soils Engineering, Boise, Idaho, 5, 6, 7 April 1971.

Project TRINIDAD, an explosively excavated railroad cut in interbedded sandstones and shales, is described in detail. The 400-ft railroad cut detonation was accomplished in December 1970 with 44 tons of aluminized ammonium nitrate slurry. The project included investigations of explosive emplacement techniques, use of explosives, design of charge arrays, swismic motions, and postshot engineering properties. Technical programs, calibration shots, and field procedures are discussed in some detail. The use of millisecond delays to reduce seismic hazards is particularly significant.

Article 17

EXPLOSIVE EXCAVATION CURRENT TRENDS

LaFrenz, R. L.

The Military Engineer, No. 413, May-June 1971

Much research has gone into interoceanic canal studies using nuclear excavation techniques. Economic and safety uncertainties still exist, waiting for experimentation. Airblast and seismic effects as well as radioactivity are major concerns.

Chemical explosives eliminate radioactivity problems. A canal, a harbor, and a railroad cut performed by the use of chemical explosives have demonstrated potential for their use. These means provide opportunity for significant cost and time savings on medium and large scale civil construction projects.

Article 18

SLOPE ANALYSIS FOR EXPLOSIVE EXCAVATIONS

Gates, R. H.

This paper was prepared for submittal to: The Proceedings of the Thirteenth Symposium on Rock Mechanics, to be held at the University of Illinois at Urbana-Champaign, Ill., August 30-September 1, 1971.

The assessment of crater slope stability requires specific information on crater geometry, geologic conditions, and material properties at the site, including seepage and weathering characteristics of the materials.

Fallback from dry rock media will behave as cohesionless material and may be studied by methods developed for the stability of rubble, talus, and rockfill. Factors

of safety for the fallback portion of a crater slope should range between 1.1 and 1.5, and the rupture zone is buttressed by the fallback.

Rupture zone materials in rock would most likely fail along surfaces of natural or blast-induced fractures if the strength of the intact rock is significantly larger than the frictional resistance to sliding along the fractures. The effects on slope stability of possible long-term changes in strength and seepage characteristics in response to weathering agents are hard to assess.

The methods of analysis of explosive excavations are continuing to improve. Limit equilibrium techniques are satisfactory for design, but the continuum mechanics techniques are helpful in the research of rock behavior.

Article 19
EXPLOSIVE EXCAVATION
LaFrenz, R. L.
For: 13th Annual Explosives Safety Seminar, San Diego, Calif., 14-16 September 1971

The explosive excavation approach to construction projects has been demonstrated on a water conveyance channel, a harbor and a railroad cut. Projects presently in progress include additional railroad cuts, a highway cut, a channel excavation, a channel widening project and several military applications.

Since the principal objective of the Corps is to develop explosive excavation as an accepted cost-competitive construction technique, future research and work will emphasize simplification and refinement of design and execution procedures. To accomplish this objective, the information must be made available to engineers in the field. To this end, a comprehensive report entitled "Explosive Excavation Technology," NCG TR-21, was recently published, including general guide specifications.

Large reductions in emplacement and explosives costs have been experienced in the past two years in the process of developing explosive excavation, and further significant reductions appear feasible. These reductions, when combined with more efficient designs and execution techniques, should continue the downward cost trend of explosive excavation. When this reducing cost trend is compared with the rising cost trend of conventional construction, the promise of significant savings in both time and money is evident for many future excavation projects.

Article 20

LARGE YIELD EXPLOSIVE CHARGES AND EFFECTS

Day, W. C.

For: 13th Annual Explosives Safety Seminar, San Diego, Calif., 14-16 September 1971

A research program in explosive excavation is providing experience in detonating relatively large charges underground at depths designed to crater or mound. Individual charge yields have ranges from about one ton to approximately 85 tons, and total detonation yields of multiple charges up to 210 tons have been fired. The explosives used in the major tests have been TNT, nitromethane, ANFO, and aluminized ammonium nitrate slurries. Charge shapes have been either spherical or cylindrical with height to diameter ratios of up to 3:1. Experience has shown that of the many explosives and blasting agents available for the main explosive excavation charges, the ammonium nitrate base explosives seem to offer the most cost advantage. The primary explosive characteristics desired are a high gas bubble energy, a high heat of detonation, an impedance ratio with the medium between 0.2 and 1.0, and a detonation pressure under 150 to 200 kbar. The explosive should have sufficient density to displace water if necessary, it should have a high-water resistance if emplaced in very damp or wet boreholes, it should be classified as an oxidizing material to minimize shipping costs, and it should have a high viscosity in the emplaced configuration when needed. With appropriate additives the ammonium nitrate base explosives can be made to meet any of the appropriate characteristics from those above that would apply in a particular case.

Effects measurements including crater dimensions, ground motion, airblast, underwater shock, water waves, and missile ranges have been made which have led to a general prediction capability. This prediction capability is continually being revised and updated as research results and new test data warrant.

Article 21

LOW COST EXCAVATION WITH LARGE EXPLOSIVES

Holmes, R. S.

This paper is to be presented at: The SME Fall Meeting and Exibit — Seattle, Washington, September 22-24, 1971

Explosive excavation using large charges offers significant cost and time savings for projects that are amenable to this technology. The Corps of Engineers is developing this technology in a very practical way; i.e., by performing experimental excavations on the sites of real projects under construction. This approach allows explosive excavation to be compared directly with conventional excavation experience on the same job.

The Corps of Engineers explosive excavation research program has made remarkable progress in cost reduction in its first two years. Today, this technology is

competitive with conventional methods of excavation for many applications. Current studies of improved techniques suggest that even further cost reductions are to be expected in the future. When this downward trend is compared with the rapidly rising cost of conventional excavation, the application of explosive excavation to a broad spectrum of future projects seems assured.

The current approach to technology development followed by EERO is to apply explosive excavation to actual projects; i.e., to execute experimental excavations which provide necessary research data and perform a useful and necessary excavation task at the same time. This procedure provides a sound basis for comparing the costs of explosive excavation techniques with more conventional methods of excavation in terms of the finished product. The postdetonation construction procedures necessary to complete the project must be considered in determining the true value of explosive excavation in project economics.

Article 22

EXPLOSIVE EXCAVATION RESEARCH: PROJECTS TUGBOAT AND TRINIDAD

LaFrenz, R. L. and Day, W. C.

American Nuclear Society Winter Meeting, October 17-21, 1971
to be published in Nuclear Technology

Large chemical explosive charges are being used in multiple charge designs in a variety of media and topographic situations to achieve actual construction projects. This program is being conducted with the realization that solving the engineering problems associated with using large point charges to achieve project objectives is a first major step toward the eventual acceptance of the use of nuclear explosives as these point charges. The target is the development of chemical and nuclear explosive excavation as accepted cost competitive construction techniques.

Projects conducted in this new approach are TUGBOAT, a small boat harbor in a coral medium at Kawaihae, Hawaii, and most recently TRINIDAD, a series of tests and railroad cuts in a sandstone and shale medium at Trinidad, Colorado. A cost analysis of these latest projects when combined with earlier experience shows a unit cost reduction trend for chemical explosive excavation compared to a unit cost increasing trend for excavation by conventional means.

Article 23

SIMULATING SUBSURFACE NUCLEAR EXPLOSIONS WITH CHEMICAL EXPLOSIVES

Leahy, E. J. and Burton, D. E.

17th Conference on Design of Experiments in Army Research, Development and Testing, October 27-29, 1971, Maryland

A series of field experiments are being designed and theoretical studies are being conducted to select a chemical explosive and to develop explosive charge configurations and synthetic fallout material to simulate subsurface, sub-kiloton nuclear cratering explosions. The studies and experiments are directed toward determining the effects, the type and degree of stemming (full stemming, water stemming, and no stemming) have on the size of nuclear pattern. Such information for detonations in a variety of geologic media is required if nuclear explosives are to be developed as a civil and military construction tool.

The problems associated with simulating these effects through the use of chemical explosives are discussed, and partial solutions are presented. The theoretical and experimental programs will study the relative effects of the different stemming configurations in the chemical explosive case and relate the results to the nuclear case. It is suggested that these investigations will lead to optimum design criteria for simulation experiments and to a means of inferring the information which cannot be simulated.

Article 24

RAPID EXCAVATION WITH EXPLOSIVES

Groves, R. H. and LaFrenz, R. L.

Civil Engineering, ASCE, April 1971

The Nuclear Cratering Group used large chemical high-explosive charges of up to 85 tons of nitromethane during the period 1962-69 as modeling charges for the AEC's nuclear excavation tests. During the conduct of these modeling tests it became obvious that explosive excavation using chemical high explosives offered the possibility of both cost and time advantages over conventional construction techniques on small to medium-sized projects.

The NCG research effort, previously dedicated to nuclear excavation, was extended in 1969 to include the development of chemical high-explosive excavation an an accepted cost competitive construction technique. Since that time significant progress has been made. Actual excavation costs, which were as high as \$8 to \$10/yd^3 during the modeling phase, have been reduced to \$1.50 to \$2.50/yd^3 based on usable cross section. Further reductions are foreseen. The economics of explosive excavation are directly related to the kind of project to which it is applied. Perhaps the greatest economic advantage is obtained when excavating a cut for a water conveyance channel. In this case, the entire explosively excavated cross section can be utilized in calculating

the cost per yard. A project requiring only excavation rather than a balanced cut and fill design is desirable, since the secondary handling of cratered material in a cut and fill design when the cut is explosively cratered reduces the economics considerably. Possibly the greatest future for the technique is in the area of marine engineering where conventional costs are high and the environmental impact of ejected material, dust, and airblast are minimized.

Article 25

THE CORPS IS PUTTING EXPLOSIVE EXCAVATION DESIGN ON A MORE SCIENTIFIC BASIS

Day, W. C.

The Explosives Engineer, February 1972

The Corps of Engineers through the Explosive Excavation Research Office, an activity of the Waterways Experiment Station, is engaged in research and development of excavation techniques using explosives. Prior to August 1971 this organization was known as the U.S. Army Corps of Engineers Nuclear Cratering Group. During the period 1962-69, many cratering explosions were executed using spherical charges of up to 85 tons of nitromethane to model nuclear excavation concepts and to develop design criteria for nuclear cratering explosions done by the Atomic Energy Commission (AEC) in the Plowshare Program. The experience gained in these modeling tests suggested that explosive excavation using large chemical explosive charges could be applied to excavation projects as an economical substitute for more traditional excavation techniques. The objective of the research program is therefore the development of explosive excavation as an accepted cost competitive construction technique.

The term "explosive excavation" as used here is meant to imply the use of larger than normal buried explosive charges to produce an excavation by fracturing and casting material into a desired configuration. It includes "throw-out cratering" as the simplest design technique but also includes "mounding," "directed blasting," and "structural excavation." The approach being used by EERL in the program is to develop design methods that make the best use of explosive energy and that minimize the use of earthmoving equipment. The literature indicates that large explosions have been used for a number of years in the Soviet Union, out of necessity, to accomplish sophisticated excavation tasks in normal construction operations. However, the technology is not well known in the U.S., and is pretty much limited to mining operations where the rock media properties are well understood and the blasting operation is a repetitive one. EERL's effort is to put the design procedure on a more general scientific base such that it can be used in normal construction projects. Systematic design procedures are being developed that use as variables such things as single charge apparent and true crater radius and depth, and overburden velocities. These variables are functions of rock properties, explosive capabilities and depth of the charge. Multiple charge designs are made by using a predictable enhancement of single charge dimensions that is

dependent on charge spacing and depth. Proper time delays in charge detonations are used to accomplish directed blasting and to reduce the magnitude of unwanted airblast and seismic signals at adjacent structures to acceptable levels. These design methods are being tested on actual prototype projects. (See the pictures and descriptions of the projects where three of the concepts, "cratering," "mounding" and "directed blasting," were tested.) The prototype projects are studied in detail and the design procedures evaluated.

This procedure of testing designs on prototype projects in the Corps of Engineers' Construction Program also provides a sound basis for comparing the costs of explosive excavation methods with more conventional methods of excavation. The cost trend for explosive excavation has been a decreasing one as design techniques have been refined. Unit cost figures are given for experiments that used the cratering and directed blasting design approach; i.e., the material was removed totally with explosive energy. In addition, a mounding project done as one of the three experiments in the Trinidad Railroad Relocation Series showed a unit cost of $\$0.79/yd^3$ for shooting the material such that it could subsequently be removed as common excavation. The experiments at Trinidad were found to be very competitive with the more conventional method of rock excavation.

EERL has recently published a report which presents the results of past work in a form usable by engineers to accomplish the design of the more simple explosive excavation projects. This report, designated Technical Report 21, "Explosive Excavation Technology," is available on request. The report will be revised as more design concepts are developed and proven, especially in the more complex directed blasting and structural excavation areas.

Article 26

PROGRESSIVE FAILURE MODEL FOR CLAY SHALE

Gates, R. H.

Paper to be submitted to USAE WES for symposium on Applications of the Finite Element Method in Geotechnical Engineering, 1-4 May 1972, at Vicksburg, Mississippi

The analysis of slopes to include the determination of stresses and displacements is an important step in better understanding of the behavior of slopes of earth material. The problems inherent in the design of slopes are augmented by new techniques of excavation such as the use of nuclear devices and chemical explosives.

The usual assumption of elastic material helps to develop the understanding desired; however, this assumption is limited in its attempt to predict the behavior of earth material. In addition to the assumption of elastic material, other stress-strain paths are considered for a frictional material whose yielding is dependent upon a yield criterion proposed by Drucker and Prager.

A stress-strain path considered in this paper simulates tests on soil and rock that show a progressive failure or strain-softening. The model uses two straight lines to represent bilinear inelastic behavior initially. The point at which the line bends is an initial yield point. The second yield or failure corresponds to the reduction in strength known as strain-softening, and the stress drops to a new yield surface represented by the residual strength, usually a considerably reduced angle of internal friction with zero cohesion. At this new stress level, the material is assumed to behave in a perfect-plastic manner. With this model both the initial state of stress and the incremental unloading of the slope are applied.

The numerical method selected was the finite element method and was applied to a continuum in plane strain. The finite element method, a displacement method of analysis, assumes linear displacement functions for triangular elements representing the continuum.

The computer program developed to make this analysis produces the stresses and displacements in addition to listing at each increment those elements that have yielded. The resulting stresses are plotted with the aid of a computer code written to contour and plot the stress fields. These stress results are also used for determining the surface with the minimum factor of safety assuming a circular failure surface. A problem was analyzed for a 45 deg slope in a semi-infinite mass. The development of the yield zone in the slope was similar to slopes experiencing progressive failure.

Article 27
ARMY DEVELOPS "INSTANT EXCAVATION"
LaFrenz, R. L.
Article for Soldiers Magazine, April 1972

Saving time, money, and the environment are popular objectives in today's society but seldom mutually obtainable. The Corps of Engineers, however, is in the process of developing a construction technique called "explosive excavation" which on selected excavation projects promises all three goals simultaneously. The approach is to bury a row or rows of large charges in a pattern to produce the desired excavation. The charges are buried at the optimum depth to move the most material. They are then detonated either simultaneously or sequentially not only to break up the material but also to move it out of the excavation at the same time. ".....Four, three, two, one, DETONATION" replaces "fire-in-the-hole" but the result is the same, the detonation of an explosive charge.

Emphasis is now on the use of chemical explosive charges in the range of 1 to 10 tons. Research was started on this technique by the Corps of Engineers and the Atomic Energy Commission in 1962 with the idea of using nuclear explosives. Chemical charges were used as modeling tools for the much larger nuclear detonations, but it soon became obvious that "chemical explosive excavation" was a technique worthy of

development in its own right. The cratering or directed blasting development, where the material is broken and moved by the same detonation, is the most spectacular form of explosive excavation. A parallel development termed "mounding," where large concentrated charges are used to fracture the material but retain it in the excavation, offers even greater economic advantages, however, in some situations. Controlled blasting techniques can be used to minimize fracturing beyond the excavation boundary when the mounding technique is used for structural excavations.

The principal advantages of explosive excavation (dollar savings, speed of construction, and environmental advantages) have varying influences on any specific project. At present, the technique has been developed to the point where it is just economically competitive with standard construction techniques but indications are that savings of over 25% will be possible on some projects when the development is complete. Not only is speed of construction an advantage in some cases where weather, project necessity, etc., are critical factors, but the reduction in heavy earthmoving or dredging equipment requirements could also be significant.

Article 28

EXPLOSIVE EXCAVATION DEVELOPMENT FOR CONSTRUCTION AND COMBAT APPLICATIONS

LaFrenz, R. L. and Day, W. C.

Annual Army Science Conference, April 1972

The Corps of Engineers, through the U. S. Army Engineer Waterways Experiment Station Explosive Excavation Research Office (formerly the Nuclear Cratering Group), is developing chemical explosive excavation as a construction technique using as a base the techniques and knowledge acquired in chemical explosive cratering tests of the nuclear excavation program. Large chemical charges are being used in multiple charge designs in a variety of media and topographic situations to achieve actual construction projects. The target is the development of chemical and nuclear explosive excavation as accepted cost competitive construction techniques.

This new technique has been demonstrated on a 1370-ft channel, a small boat harbor in coral medium in Hawaii, three railroad cuts through a sandstone and shale medium in Colorado and a channel plug project in North Carolina. A cost analysis shows a unit cost reduction trend for chemical explosive excavation compared to a unit cost increasing trend for excavation by conventional means.

Military research using explosive excavation is also conducted to apply this technique to both military engineering for combat purposes and military construction. Considerable research has also been conducted to develop a chemical explosive configuration to simulate ADM's. The information gained from both the civil and military research is integrated into the overall development of explosive excavation.

Article 29

EXPLOSIVE EXCAVATION RESEARCH

Gates, R. H.

North American Rapid Excavation and Tunneling Conference, April 1972

The Corps of Engineers through the Explosive Excavation Research Office (formerly the Nuclear Cratering Group), an Activity of the Waterways Experiment Station, is developing chemical explosive excavation as a construction technique for use on Civil Works projects using as a base the techniques and knowledge acquired in chemical explosive cratering tests of the nuclear excavation program. Large chemical charges are being used in multiple charge designs in a variety of media and topographic situations to achieve actual construction projects. The target is the development of chemical and nuclear explosive excavation as accepted cost competitive construction techniques.

This new technique has been demonstrated on a 1370-ft channel at Fort Peck, Montana and on two actual Civil Works projects: Project TUGBOAT, a small boat harbor in coral medium at Kawaihae, Hawaii, and most recently Project TRINIDAD, three railroad cuts through a sandstone and shale medium at Trinidad, Colorado. A cost analysis of these latest projects, when combined with earlier experience, shows a unit cost reduction trend for chemical explosive excavation compared to a unit cost-increasing trend for excavation by conventional means. The railroad cuts at Trinidad are judged to be the first really competitive use of the technique. Additional projects include highway cuts, channels, underwater rock removal and harbors. Explosive excavation also offers significant construction time, and environmental advantages on some projects over conventional techniques.

Military research using explosive excavation is also conducted to apply this technique to both military engineering for combat purposes and military construction. Considerable research has also been conducted to develop a chemical explosive configuration to simulate ADM's. The information gained from both the civil and military research is integrated into the overall development of explosive excavation.

Basic research is being conducted in both controlled blasting and directed blasting to reduce blast disturbance and permit the use of explosive excavation or mounding for sensitive projects. Additional research is directed toward matching explosive properties to the rock being excavated to obtain the best energy balance between shock and heaving.

III. Cross References

This section is made up of three indexes: a subject index, an author index, and a title index. The subject listings of publications are as follows:

ADM Employment
Airblast
Canal Studies
Conventional Construction
Contained Explosives
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